PhD THESIS

The Role of Maximum Strength, Explosive Strength, Reactive Strength and Deceleration in Rehabilitation and Performance

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January 2019

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Declaration

I hereby certify that this materal which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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January 8th, 2019

Acknowledgements

Every man should pull a boat over a mountain – Walter Herzog

Over the last five years, I feel that this Walter Herzog quote captures an element of this achievement. I undertook my PhD with the express aim of improving myself as a practitioner. While it has been challenging, I feel I have achieved this aim and I have very much enjoyed the journey. Pulling a boat over a mountain is hard and I would not have completed this thesis without a combination of grit, determination and ignorance on my part. However, far from simply patting myself on the back, this would not have been possible were I to have undertaken it alone.

Whether or not nature or nurture are responsible for the development of the traits I feel I displayed, it does not matter. I have my parents to thank for them. To my mum and dad I say thank you for all the lessons you taught me, for the opportunities you gave to me and for your selflessness in doing so, and for the love and support you have shown me throughout the last 35 years.

To Dr Andy Franklyn-Miller and Dr Eanna Falvey, thank you for taking a chance on me and giving me an opportunity to do this. Thanks for the pats on the back and the kicks in the ass, the big 5 in Cape Town, the tapas in Barcelona and the sightseeing in Milan.

To my supervisor Dr Kieran Moran, your patience, encouragement, guidance, teaching, empathy and support are why I am able to write these acknowledgements at the end of this journey. Thank you for every corrected spelling mistake, every word of encouragement, every lesson you taught me and every ‘just so you know…’.

To Enda King, Dr Chris Richter, Sam Baida, Colm Fuller, Edel Fanning and Dr Shane Gore, thank you for all the support. I cannot count the number of coffees, pints and occasional old fashioneds that have accompanied your words of support, without which this journey would have been so much harder. I hope I have, and can continue to return the favour to you all.

To my brothers Eoin and Philip, and my sister Fiona. Thank you for daring to ask the dreaded question ‘How is the PhD coming along?’. While I may have been a bit of a dick answering it, it was always appreciated. For the regular phone and video calls, and the visits and holidays, thank you. It has not always been easy having so many miles between us, but you were always…almost always, able to give me a lift.

To my girlfriend Sara, thank you for taking my mind off it and for listening when I couldn’t. For trips away, for walks in the country, for meals for two and for school night pints. For being the light at the end of the tunnel and helping me over the line, thank you xx.

Abstract

Introduction: Deficits in neuromuscular strength qualities are common across a range of musculoskeletal injuries and are usually measured about a single joint (Petersen *et al.*, 2014). Neuromuscular strength qualities can also correlate with athletic performance, however, these are generally measured using whole-body tasks (Spiteri *et al.*, 2015). The aim of this thesis is to explore the role of whole-body neuromuscular strength qualities in the rehabilitation of chronic musculoskeletal conditions and examine if the same strength qualities are important for athletic performance.

Methods: This thesis incorporates work from six investigations including: two rehabilitation intervention studies, three exploratory biomechanical analyses and one methodological study. It incorporates novel techniques employed in the biomechanical analysis of a series of athletic tasks.

Results and Conclusion: Whole-body resistance training interventions demonstrated significant improvements in low back pain outcomes and reduced fat infiltration within lumbar musculature but without improvements in maximum or explosive strength. Athletes with athletic groin pain demonstrated deficits in force production capacity in maximum, explosive and reactive strength, deceleration and cutting tasks compared to non-injured athletes. Including additional explosive strength training in a rehabilitation program led to altered strategies during cutting and reduced return to play times compared to a standard rehabilitation program. The technical ability to produce horizontal force, rather than the amount of force, determines performance during cutting. This is achieved by maintaining a low centre of mass and a wider foot position while utilising shorter ground contact times.

The results from this PhD thesis have made novel contributions in relation to both rehabilitation from chronic musculoskeletal conditions and athletic performance. The findings will help to inform clinical practice and aid in the design of future research.

List of abbreviations

CMJ – countermovement jump

DJ – drop jump

SJ – squat jump

VJ – vertical jump

GCT - ground contact time

AP – average power

PP – peak power

PF – peak force

PV – peak velocity

MVC – maximum voluntary contraction

GRF – ground reaction forve

RSI - reactive strength index

RM – repetition maximum

RFD/RTD – rate of force/torque development

EMG – electromyography

MRI – magnetic resonance image

ES – effect size

RR – risk ratio

OR – odds ratio

HR – hazard ratio

CI – confidence interval

ACLR – anterior cruciate ligament reconstruction

IMTP – isometric mid-thigh pull

HAGOS – hip and groin outcome score

ODI – Oswestry disability index

QOL – quality of life

ROM – range of motion

A/P – anterior posterior

List of publications

AN INTERACTIVE SEGMENTATION TOOL FOR QUANTIFYING FAT IN LUMBAR MUSCLES USING AXIAL LUMBAR-SPINE MRI (2015). ANTONY, J., MCGUINNESS, K., WELCH, N., COYLE, J., FRANKLYN-

MILLER, A., O'CONNOR, N.E. AND MORAN, K. *INNOVATION AND RESEARCH IN BIOMEDICAL ENGINEERING.* 1. PP. 1-12

THE EFFECTS OF A FREE-WEIGHT-BASED RESISTANCE TRAINING INTERVENTION ON PAIN, SQUAT BIOMECHANICS AND MRI-DEFINED LUMBAR FAT INFILTRATION AND FUNCTIONAL CROSS-SECIONAL AREA IN THOSE WITH CHRONIC LOW BACK PAIN (2015). WELCH, N., MORAN, K., ANTONY, J., RICHTER, C., MARSHALL, B., COYLE, J., FALVEY, E. AND FRANKLYN-MILLER, A. *BMJ OPEN SPORT & EXERCISE MEDICINE*. 1(1). PP 1-10

List of submissions in review

PRINICPAL COMPONENT ANALYSIS OF THE ASSOCIATIONS BETWEEN KINETIC VARIABLES IN CUTTING AND JUMPING, AND CUTTING PERFORMANCE OUTCOME - WELCH, N., RICHTER, C., FRANKLYN-MILLER, A. AND MORAN, K. *JOURNAL OF STRENGTH AND CONDITIONING RESEARCH.*

PRINCIPAL COMPONENT ANALYSIS OF THE BIOMECHANICAL FACTORS ASSOCIATED WITH PERFORMANCE DURING CUTTING – WELCH, N., RICHTER, C., FRANKLYN-MILLER, A. AND MORAN, K. *JOURNAL OF STRENGTH AND CONDITIONING RESEARCH.*

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THE EFFECTS OF A FREE-WEIGHT BASED STRENGTH TRAINING INTERVENTION ON PAIN, LUMBAR FAT INFILTRATION AND BIOMECHANICS (2015). WELCH, N., FALVEY, E., MARSHALL, B., ANTONY, J., GORE, S., RICHTER, C., MORAN, K. AND FRANKLYN-MILLER, A. *EUROPEAN LEAGUE AGAINST RHEUMATISM.*

THE RELATIONSHIP BETWEEN DROP JUMP AND CHANGE OF DIRECTION PERFORMANCE (2017) WELCH, N., RICHTER, C., MORAN, K., FALVEY, E. AND FRANKLYN-MILLER, A. *ISOKINETICS CONFERENCE.*

FAT QUANTIFICATION IN MRI-DEFINED LUMBAR MUSCLES (2014). ANTONY, J., MCGUINNESS, K., WELCH, N., COYLE, J., FRANKLYN-MILLER, A., O'CONNOR, N.E. AND MORAN, K. 4TH INTERNATIONAL CONFERENCE ON IMAGE PROCESSING THEORY, TOOLS AND APPLICATIONS

List of studies to be submitted

A COMPARISON OF GROUND REACTION FORCE BASED VARIABLES DURING CUTTING, MAXIMAL STRENGTH AND EXPLOSIVE STRENGTH TASKS IN THOSE WITH AND WITHOUT ATHLETIC GROIN PAIN - WELCH, N., RICHTER, C., FRANKLYN-MILLER, A. AND MORAN, K.

THE EFFECT OF EXPLOSIVE STRENGTH TRAINING IN THE REHABILITATION OF ATHLETES WITH ATHLETIC GROIN PAIN - WELCH, N., RICHTER, C., FRANKLYN-MILLER, A. AND MORAN, K.

List of Tables

List of Figures

1 Introduction

Chronic musculoskeletal conditions are prevalent in society affecting non-athletic and athletic populations. Among many factors, maximum strength has been suggested as contributing to such conditions and has formed a part of many rehabilitation interventions. In healthy populations, strength increases are commonly sought using whole-body free-weight resistance training. However, this method isn't commonly used in rehabilitation of chronic conditions with isolated exercises being the most prevalent.

In addition, in athletic populations, explosive strength, reactive strength and deceleration, alongside maximum strength are known to be important for performance. However, the role maximum strength, explosive strength, reactive strength and deceleration play in rehabilitation of chronic musculoskeletal conditions in athletic populations and their relationship to return to performance is not well understood.

This collection of studies will seek to understand the effectiveness of whole-body free-weight resistance training in rehabilitation from chronic musculoskeletal conditions (both low back pain and athletic groin pain). In addition, for athletic populations, it will examine the roles that maximum strength, explosive strength, reactive strength and deceleration play in rehabilitation and their relationship with performance.

Chronic low back pain is one of the most common chronic musculoskeletal conditions with a point prevalence rate of 18.1% and 1 year prevalence of 38.1% (Hoy *et al.*, 2010), it affects populations of all activity levels but it's prevalence increases with age, peaking at 60-65 years old (Hoy *et al.*, 2010; Fett, Trompeter and Platen, 2017). With such a high prevalence rate affecting such a broad population, a large number of factors have been associated with low back pain, including: patho-anatomical factors (Hancock *et al.*, 2012), lumbar muscle deconditioning (Steele, Bruce-Low and Smith, 2014a), biomechanical factors (Shum, Crosbie and Lee, 2005), motor control factors (van Dieën, Selen and

Cholewicki, 2003), posture (Dankaerts *et al.*, 2006) and psychosocial factors (O'Sullivan, 2005). One of the primary conservative interventions that has been shown to be effective is exercise therapy (Hayden *et al.*, 2005). These exercise interventions include aerobic exercise, stretching, Pilates, motor patterning/coordination, isolated lumbar strengthening and whole-body strength training. In a review of exercise interventions, Searle et al (Searle *et al.*, 2015) found small but significant effects for strength training and coordination training with larger effect sizes seen among the strength training interventions. While in the field of strength and conditioning whole-body free-weight strength training is used to obtain increases in strength and to alter muscular conditioning, its use does not appear to be common in rehabilitation from chronic low back pain. Further understanding of whether changes in whole-body strength are related to improvements in this chronic condition is needed.

Chronic musculoskeletal conditions are also seen in athletic populations. Athletic groin pain is common in athletes partaking in multiple field sports including Gaelic Football (Wilson *et al.*, 2007), Rugby Union (Brooks *et al.*, 2005) and Australian Rules Football (Orchard and Seward, 2002). As with low back pain, patho-anatomical (Falvey, King and Kinsella, 2015), local muscle conditioning (Whittaker *et al.*, 2015), biomechanical (Whittaker *et al.*, 2015) and psychosocial (King *et al.*, 2018) factors are thought to contribute to this chronic condition. Exercise interventions are recommended as the primary option following a period of rest (Jansen *et al.*, 2008). As with low back pain, interventions have in the main not used whole-body free-weight strength training, instead focusing on local hip and abdominal muscle strengthening, balance training and gradual return to running and cutting (Holmich *et al.*, 2010; Weir *et al.*, 2011; Charlton *et al.*, 2017). An understanding of the effectiveness of whole-body free-weight resistance training in rehabilitation is warranted.

In addition to maximum strength, cutting and explosive strength, reactive strength and deceleration qualities are viewed as important in field sports athletes (Sheppard and Young, 2006; Brughelli *et al.*, 2008). While cutting has been examined in relation to groin pain, explosive strength, reactive strength and deceleration have not. The main outcome measures in intervention studies among populations rehabilitating from injury are centred around pain, disability and return to play. However, it is important to recognise that when athletic populations return from chronic conditions, there is an aim to return to similar performance levels to those prior to the injury. There is little to suggest in the literature that much work has been done to determine whether rehabilitation interventions among field sports athletes returning from chronic conditions enhance or degrade the performance in cutting. There is a tendency for work to focus on the injurious mechanisms and how to alter them to reduce risk of re-injury and enhance return to play (Brown, Brughelli and Hume, 2014; Pappas *et al.*, 2015) rather than improve performance. Although alterations to biomechanical variables have been observed during rehabilitation that have been associated with performance (King *et al.*, 2018), the whole-body maximum strength, explosive strength, reactive strength and deceleration qualities, and performance in cutting itself have not. As discussed above, the roles that maximum strength, explosive strength, reactive strength and deceleration play in rehabilitation are often overlooked and determining whether these factors are important in returning an athlete to their sport and higher levels of performance is important.

To this end, the scope of the studies included in this piece of work is to:

1. understand the role of whole-body maximum and explosive strength in rehabilitation from low back pain.
2. determine the role of explosive strength, reactive strength and deceleration in rehabilitation from athletic groin pain.
3. understand if the roles of maximum strength, explosive strength, reactive strength and deceleration for cutting performance differ from those required for rehabilitation from athletic groin pain.

To address the above, five studies were undertaken:

Study 1 is an intervention study examining the effects of a whole-body free-weight resistance training intervention on pain, disability, quality of life, MRI-defined lumbar fat infiltration and functional cross sectional area, squat biomechanics and whole-body maximum and explosive strength in those with low back pain. This was undertaken with 26 participants who completed 16 weeks of whole-body free-weight resistance training. Large reductions in pain and disability, significant reductions in lumbar fat infiltration, increased functional cross sectional area were found. However, no change in whole-body maximum strength or explosive strength was seen following the intervention. This appears to be the first study to demonstrate reductions in lumbar fat infiltration and increased functional cross sectional area following a whole-body free-weight resistance training intervention in those with low back pain.

Study 2 is a cross-sectional study examining the differences in maximum strength, explosive strength, reactive strength, deceleration and cutting biomechanics between those with and without athletic groin pain. This study included 28 participants with athletic groin pain and 25 non-injured field sports athletes. Between-group differences were examined using a principal component analysis with simulation approach. Injured athletes demonstrated deficits in cutting performance, maximum strength, explosive strength, deceleration and reactive strength. These differences are likely due to a combination of deconditioning due to reduced training loads and or pain inhibition, and offloading strategies to reduce pain.

Study 3 is an intervention study that sought to examine the effects of additional explosive strength training with a standard method of groin rehabilitation on return to play time, maximum strength, explosive strength, reactive strength and deceleration, and biomechanics of cutting in those with chronic groin pain. Participants were split into two groups: a no-jump intervention group who underwent a standardised rehabilitation protocol and a jump intervention group who completed the same standardised rehabilitation but with additional explosive strength training. The jump intervention group demonstrated greater reductions in ground contact time and greater improvements in concentric force production during the cuts, lower increases in horizontal force during a single-leg squat jump, greater increases in deceleration and faster return to play than the no jump intervention group.

Study 4 is a cross-sectional study examining the ground reaction force based performance determinants of cutting and the relationship between maximum strength, explosive strength, reactive strength and deceleration, and cutting performance. Twenty-five elite gaelic football players had biomechanical and performance data captured during a series of maximum strength, explosive strength, reactive strength, deceleration and cutting tasks. A principal component analysis and simulation approach was used. The results showed that the ability to produce horizontal force during a short ground contact time was a significant factor in cutting tasks. It was also shown that whole-body maximum strength and explosive strength had no relevant relationship with cutting performance while reactive strength and deceleration did.

Study 5 is a cross-sectional study examining the biomechanical factors associated with performance during cuts of differing angles. Twenty-five elite gaelic football players had biomechanical and performance data captured during 45° and 110° cuts. A principal component analysis and simulation approach was taken, along with a correlation analysis between cutting performance outcome and biomechanical variables in the cuts. Maintaining a low centre of mass, maintaining distance between the foot and centre of mass and utilising short ground contact times were observed to relate to better performance in both cuts. Additionally, leaning in the direction of the cut was observed to relate to better performance in the 110° cut. These findings assist practitioners in developing the key technical components to enable athletes to improve cutting performance.

2 Strength qualities and testing in rehabilitation and performance

2.1 Maximum strength

Maximum strength is an important athletic quality in relation to rehabilitation from injury (Reiman and Lorenz, 2011) and athletic performance (Suchomel, Nimphius and Stone, 2016). This section will look at the methods of measuring maximum strength and the rationale for the selection of certain testing methods. It will then look at the relationships that exist between maximum strength and both rehabilitation and performance arguing that it is an important quality across both areas and a necessary measure when considering both.

2.1.1 Methods of measuring maximum strength

Maximum strength has been defined as the ability to exert force (Stone, 1993) against an external object or resistance. It can be measured in many ways using dynamic or isometric methods with strong correlations seen between the two in the literature (Mcguigan and Nelson, 2010; Bazyler, Beckham and Sato, 2015). Isometric and dynamic methods have also been shown to be reliable measures of maximum strength (Drouin *et al.*, 2004; Haff *et al.*, 2014; Comfort and McMahon, 2015). Maximum strength is generally tested dynamically using repetition maximum tests that involve a participant gradually working up to the maximum weight they can lift for a given exercise for a specified number of repetitions. Isokinetic strength testing is an alternative dynamic method of determining maximum strength whereby the participant attempts to move the arm of the isokinetic dynamometer as hard as possible and the peak torque is taken as their maximum strength. The isokinetic dynamometer is also used to measure isometric strength, and is commonly used for movements performed about a single joint, for example maximum knee flexion or knee extension strength. Maximum strength can also be measured using the isometric squat and isometric mid-thigh pull (IMTP), both are frequently selected due to their similarity with athletic postures and the ability to get highly reliable measurements (Haff *et al.*, 2014; Bazyler, Beckham and Sato, 2015). The IMTP in particular now appears common among athletic populations to measure maximum strength as well as rate of force development (Juneja, Verma and Khanna, 2010).

A variety of factors will influence the selection of the tests used to measure maximum strength. Access to equipment is one. Isokinetic dynamometers and force plates (required for the IMTP) are expensive pieces of equipment and are not accessible to everyone. In contrast, the barbells and weights needed for repetition maximum testing are available in most gyms and are relatively cheap, and therefore are more readily available. Repetition maximum testing using dynamic methods requires a high degree of competency in the tested movement to attain a true measure of maximum strength and to reduce the risk of injury that could be associated with maximally testing an unfamiliar movement pattern. This differs from isokinetic and isometric methods as no control of movement is required as the equipment guides the movement path. As a result, well-trained athletes are often the participants in performance studies that incorporate repetition maximum strength testing. Performance test selection with these populations is sometimes determined by data collection from previous testing batteries to maintain consistency of data collection longitudinally amongst an athlete pool. The amount of available time for testing is also relevant with this population. For example, changing the maximum strength test with a group of athletes where many years of test data is present could limit the usability of historical data. Furthermore, with well-trained athletes who have a comprehensive training and competition schedule, there is a finite amount of time that can be devoted to testing so as not to encroach on that schedule. Using methods that are time efficient for staff and athletes is therefore important. For example, multiple stations to test a squat 3RM could be set up to test a number of athletes simultaneously whereas if only one isokinetic dynamometer is available then testing of a group of athletes may need to take place over a number of days. However, it could be argued that isometric tests may be a safe and valid measure in rehabilitating populations as there is much less technical challenge offered potentially reducing injury risk. In trained populations there is less technical skill required in an isometric test and so isometric testing may act to control for differences in skill.

2.1.2 The role of maximum strength in rehabilitation

Maximum strength training is widely used for rehabilitation from multiple musculoskeletal conditions (Howe *et al.*, 2011; Kristensen and Franklyn-miller, 2012). This is used to restore maximum strength following an initial strength loss generally seen following acute injury (Warren *et al.*, 2017). There is a very large body of research that examines the role of maximum strength in rehabilitation and its relationship with injury. As such, this section will examine the systematic reviews that exist (shown in Table 1 below) in the area and will highlight the importance of considering maximum strength as a measure throughout rehabilitation from injury. Seventeen systematic reviews were found that investigated maximum strength training, the aim of which is to increase maximum strength, in relation to injury and rehabilitation. Eleven studies investigated the effects of strength training on pain and function, ten of which demonstrated positive effects ranging from small to very large for both pain (ES = 0.18 to 5.3) and function (ES = 0.08 to 1.02) (Fransen *et al.*, 2009, 2014; Latham and Liu, 2010; Gaida and Cook, 2011; Kristensen and Franklyn-miller, 2012; Zacharias *et al.*, 2014; Rio *et al.*, 2015; Santos *et al.*, 2015; Searle *et al.*, 2015; Charlton *et al.*, 2017). Two of the seventeen studies examined the effects of strength training on muscle strength alongside bone mineral density finding strong effects for improvements in both among injured populations (Howe *et al.*, 2011; ter Stege *et al.*, 2014). Two other studies examined the relationship between strength and injury risk finding links between higher strength levels and reduced injury risk (Al Attar *et al.*, 2017; de la Motte *et al.*, 2017). One study found that strength deficits exist following ACL reconstruction (Petersen *et al.*, 2014) and one final study observed that there is no secondary drop in strength following acute injury (Warren *et al.*, 2017). Only one review found no relationship between strength measures and injury when examining hamstrings (Green, Bourne and Pizzari, 2017).

With regard to injury rehabilitation, maximum strength training has been found to be an effective treatment tool in achilles (Rio *et al.*, 2015) and patellar tendon rehabilitation (Gaida and Cook, 2011) where it is thought to effect muscle and tendon physiology and potentially aberrant motor patterns. Post-operative muscle strength has been shown to reduce following anterior cruciate ligament reconstruction (ACLR) (Petersen *et al.*, 2014) suggesting interventions to increase maximum strength should play a part in rehabilitation from the surgery. Strength training is advocated as a method of developing bone mineral density in the spine and the neck of the femur in osteoporotic populations (Howe *et al.*, 2011), it is regarded as the most effective exercise treatment for those with chronic low back pain (Searle *et al.*, 2015) and is an effective treatment for those with knee and hip osteoarthritis (Fransen *et al.*, 2009, 2014; Latham and Liu, 2010). Santos et al (Santos *et al.*, 2015) found positive effects from hip strengthening interventions in those with patellofemoral pain. Kristensen & Franklyn-Miller (Kristensen and Franklyn-miller, 2012) found positive effects for strength training on a pain and function in forty-nine out of the fifty-one studies included in their systematic review. This systematic review covered chronic low back pain, tendinopathies, knee osteoarthritis, anterior cruciate ligament reconstruction surgery and hip replacement surgery. The above sixteen of seventeen reviews highlight the effectiveness of strength training interventions across a broad range of musculoskeletal conditions. As such, strength training should be considered a worthwhile target for musculoskeletal rehabilitation.

Strength training has also been suggested to be an important quality in order to help mitigate risk of injury. De la Motte et al (de la Motte *et al.*, 2017) found lower levels of strength associated with greater risks of musculoskeletal injury (OR = 0.58 to 8.8; RR = 0.12 to 2.61; HR = 0.35 to 17.4). Hamstring strengthening has also been shown to reduce risk of hamstring injury (IRR = 0.49) (Al Attar *et al.*, 2017). Elsewhere, strength of the quadriceps and hamstrings have been shown to be an important part of achieving good outcomes and reducing risk of re-injury following ACLR (Moisala *et al.*, 2007; Undheim *et al.*, 2015). In upper limb athletes, muscle strength imbalances about the shoulder have been shown to increase the risk of injury (Edouard and Calmels, 2013). It has been suggested that strength training should form part of training programs to help reduce risk of anterior cruciate ligament and hamstring injury (Opar *et al.*, 2015; Monajati *et al.*, 2016) and low levels of hip adductor strength have been identified as a risk factor in groin and hip injuries (OR = 4.28 to 14.0) (Ryan, DeBurca and Mc Creesh, 2014; Whittaker *et al.*, 2015). Deconditioning through both muscle atrophy and reduced strength of the lumbar musculature has been associated with low back pain (significantly lower maximum strength 17 to 48% compared to controls) with the use of strength training advocated to potentially reduce the risk of the development of low back pain (Steele, Bruce-Low and Smith, 2014a). It has also been shown to be a safe and effective tool as part of multi-faceted (including maximal strength, reactive strength and movement control) training interventions in reducing risk of injury in younger athletes (Faigenbaum and Myer, 2012) and older college level athletes (Suchomel, Nimphius and Stone, 2016). Only one review was found that demonstrated a weak relationship between greater levels of strength and injury (Green, Bourne and Pizzari, 2017). It appears a consistent finding that maximum strength and training to increase maximum strength is an important aspect of rehabilitating and preventing a wide range of musculoskeletal injuries and conditions. This is true regardless of the age or activity profile of those injured (however, gaps in the literature exist and will be examined in later sections in relation to both Low back pain and Athletic groin pain). Strength training should therefore form a part of interventions designed to optimise recovery from musculoskeletal injury.

Table 1: Reviews investigating the relationship between maximal strength and injury.

Author	**Injury**	**Review type**	**Number of studies reviewed**	**Results**
Searle et al 2015 (Searle *et al.*, 2015)	Low back pain interventions.	Systematic review and meta-analysis.	39 studies, 11 of these on strength training.	Strength training had a moderate positive effect (ES = 0.5 using Cohen's *d*).
Latham et al 2010 (Latham and Liu, 2010)	Knee and hip osteoarthritis interventions.	Meta-analysis.	8 studies.	Strength training had a small positive effect (ES = 0.33 using Cohen's *d*)
Fransen et al (Fransen *et al.*, 2009)	Knee osteoarthritis interventions.	Cochrane review.	54 studies.	Land based exercises, of which strength training was one, had a moderate positive effect (ES = -0.74 to -0.52 using Cohen's *d*).
Fransen et al (Fransen *et al.*, 2014)	Hip osteoarthritis interventions.	Cochrane review.	10 studies.	Land based exercises, of which strength training was one, had a small to moderate effect for pain (ES = -1.08 to -0.18 using Cohen's *d*) and function (ES = -1.02 to -0.08 using Cohen's *d*).

Charlton et al 2017 (Charlton *et al.*, 2017)	Groin pain interventions.	Critical and systematic review.	3 studies, 9 case studies and series.	Beneficial effect of training interventions targeting hip and abdominal musculature.
Rio et al (Rio *et al.*, 2015)	Achilles tendinopathy interventions.	Narrative review.	N/A	A combination of strength training with tendon neuro-plastic training instead of strength training by itself may be more efficacious in rehabilitating achilles tendinopathy.
Gaida & Cook (Gaida and Cook, 2011)	Patellar tendinopathy interventions	Critical review.	32 studies	Nine studies showed improvements in outcome with strength training.
Howe et al (Howe *et al.*, 2011)	Osteoporosis interventions.	Cochrane review.	43 studies.	Strength training had a large positive effect for bone mineral density of neck of the femur was strength training (ES = 1.31 using Cohen's *d*) and of the spine (ES = 3.22 using Cohen's *d*).
Green et al (Green, Bourne and Pizzari, 2017)	Hamstring injury prediction.	Systematic review and meta-analysis.	12 studies	Strength had a small positive effect (ES = -0.17 to 0.14 using Cohen's *d*). Hamstring strength asymmetries had a moderate

				positive effect (ES = -0.55 to -0.36 using Cohen's *d*).
Santos et al (Santos *et al.*, 2015)	Patellofemoral pain hip strengthening interventions.	Systematic review.	18 studies.	Strength interventions had a small to very large positive effect (ES = -5.3 to - 0.3 using Cohen's *d*).
Kristensen & Franklyn-Miller (Kristensen and Franklyn-miller, 2012)	Musculoskeletal rehabilitation.	Systematic review.	51 studies.	39 studies showed positive effects of strength training on pain and/or function and other variables. Six studies showed positive changes in strength and/or muscle cross-sectional area alone. Two articles found no positive effects of strength interventions.
De la Motte et al (de la Motte *et al.*, 2017)	Strength and injury risk.	Systematic review.	45 studies.	Lower strength had a moderate to strong risk injury (OR = 0.58; RR = 0.12 to 2.2; HR = 0.35 to 2.2). Lower isokinetic strength associated with knee and ankle injuries (OR = 0.98 to 8.8; RR = 1.63 to 2.61; HR = 17.4).

Al Attar et al (Al Attar *et al.*, 2017)	Hamstring prevention.	Systematic review and meta-analysis.	15 studies.	Positive effect for strength interventions (IRR = 0.49).
Zacharias et al (Zacharias *et al.*, 2014)	Knee and hip osteoarthritis interventions.	Systematic review and meta-analysis.	40 studies.	Strength training had a moderate to strong positive effect (ES = 0.50 to 1.53 using Cohen's *d*).
Ter Stege et al (ter Stege *et al.*, 2014)	Knee injury interventions for risk factors.	Systematic review.	35 studies.	Strength interventions effective in increasing hamstring/quadriceps strength ratio, reducing knee valgus and reducing knee anterior tibial shear.
Warren et al (Warren *et al.*, 2017)	Secondary loss of strength following muscle injury.	Systematic review and meta-analysis.	223 studies.	Trivial effect for strength reduction (ES = 0.07 using Cohen's *d*).
Petersen et al (Petersen *et al.*, 2014)	ACL reconstruction strength loss.	Systematic review.	61 studies.	Strength deficits observed about the knee and hip (16.9 to 43%) following surgery

CI - confidence interval, ES - effect size, HR - hazard ratio, RR - risk ratio, OR - odds ratio. Some studies were included within multiple reviews.

2.1.3 The role of maximum strength in cutting performance

This section will examine the relationships between maximum strength and athletic performance in cutting. It will show that, similar to other measures of athletic performance (Suchomel, Nimphius and Stone, 2016), there is a widespread finding that a significant relationship exists between measures of maximum strength and cutting performance.

Sixteen studies (summarised in Table 2) were found that investigated the relationship between maximum strength and cutting performance outcomes. Overall, the literature points towards a strong positive correlation between maximal strength and cutting performance. Eleven of the sixteen studies investigating the relationship between maximum strength and cutting found significant positive correlations with performance (r = 0.5 to 0.94) (Wisløff *et al.*, 2004; Peterson, Alvar and Rhea, 2006; Hori *et al.*, 2008; Jones, Bampouras and Marrin, 2009; Nimphius, McGuigan and Newton, 2010; Chaouachi *et al.*, 2012; Spiteri *et al.*, 2014; Swinton *et al.*, 2014; C Thomas *et al.*, 2015; Delaney *et al.*, 2015; Thomas, Dos'Santos, *et al.*, 2016). One other investigated the differences in cutting performance between stronger and weaker athletes finding that stronger athletes produced higher ground reaction forces during cutting compared to weaker athletes (ES = 0.98 to 1.7) (Spiteri *et al.*, 2013). Another study examined 505-test performance finding that maximum strength in a leg extension task was one of eight factors that explained 99% of the variance in 505-test performance (Emmonds *et al.*, 2017). Three studies found no significant relationship between maximum strength and cutting performance (Markovic, 2007; Chaouachi *et al.*, 2009; Young, Miller and Talpey, 2015). Of those studies that found significant correlations, six used the 505-test as their measure of cutting performance (a review of methods of measuring cutting performance can found below in section 3.1) and another two used another variation of a 180° cut. The other three studies used the T-test, which involves a forward run, followed by lateral shuffling movements followed by a backward run. Each of these tests requires a heavy deceleration where the athlete reaches zero velocity in one movement plane prior to acceleration in a new movement plane. There are large eccentric and concentric force production demands to doing this, which are likely to explain the significant relationships between performance outcome and maximum strength.

Of those studies that found no significant relationship between maximum strength and cutting performance, one measured cutting performance using planned and unplanned 45° cuts (Figure 1) (Young, Miller and Talpey, 2015).

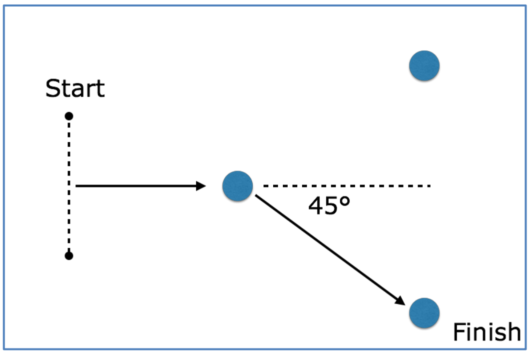


Figure 1: The layout of a 45° cut test

It is possible that the task demands of the cuts used, which require less deceleration than cuts of greater angle, meant that maximum strength was a less relevant quality. It is known that cuts of shallower angle (e.g. 45° versus 90°) have shorter ground contact times, in both the approach and cut steps, compared to greater angles (Havens and Sigward, 2015c) and therefore a shorter time to express force is present. This is relevant as producing maximum force takes upwards of 250ms (Kawamori *et al.*, 2006) meaning that shallower cuts may not allow, or require, athletes to produce maximal force; this would suggest that explosive strength abilities may be more important than maximum strength (this is reviewed in section 2.2.3). Of the remaining two studies that found no relationship, one cited the fact that the tested population were elite basketballers (Chaouachi *et al.*, 2009) and that their high proficiency in technique during lateral movements may have negated the strength demands. The other tested a predominantly untrained population who were both unfamiliar with maximum strength testing and cutting tasks. Given the broad range of tests used to measure both maximum strength and cutting performance and the general consistency in the finding of a significant relationship, it can be concluded that maximum strength is a relevant quality for cutting performance. However, to fully understand the relationship, further work using a variety of cutting angles and different deceleration and acceleration demands is needed.

2.1.4 Conclusion

The ability to produce maximum force is important in both athletic performance and rehabilitation from injury. Often though, the methods for testing and training these populations vary. Many rehabilitation studies use open chain and or machine based exercises to measure maximal strength. In contrast, performance studies commonly use whole-body maximal strength measures (Suchomel, Nimphius and Stone, 2016). For example, in low back pain, isokinetic lumbar extension strength is used regularly (Steele, Bruce-Low and Smith, 2014b) and in ACL research isokinetic dynamometry is commonplace (Undheim *et al.*, 2015). However, very little research exists into the production of force through the body as a whole in injured populations. Further research is needed to understand the role of whole-body maximal strength in rehabilitation from injury.

Table 2: Studies investigating the relationship between maximal strength and cutting performance.

Author	**Participants**	**Study Design**	**Performance test**	**Results**
Delaney et al 2015 (Delaney *et al.*, 2015)	31 male professional rugby league players.	Cross sectional study. Correlation between physical qualities and cut performance.	505-test turning off dominant (D) and non-dominant (ND) legs, 3RM back squat.	Large negative correlation between 505-test performance and relative strength (r = -0.5). Regression analysis showed relative strength and max speed explained 61% of the variance in 505-test performance.
Hori et al (Hori *et al.*, 2008)	29 male semi-professional AFL.	Cross sectional study. Correlation between hang clean, sprint, jump and cut performance.	1RM front squat, 5-5 cutting.	Moderate to large positive correlation between absolute and relative strength and 5-5 cutting performance (r = -0.51 to -0.37).
Jones et al (Jones, Bampouras and Marrin, 2009)	5 female and 33 male university students.	Cross sectional study. Correlations between physical tests and cut performance.	505-test, isokinetic leg press, knee extension and knee flexion.	Moderate to large negative correlation between strength and 505-test performance (r = -0.63 to -0.37).

Nimphius et al (Nimphius, McGuigan and Newton, 2010)	10 female softball players.	Cohort study. Measurements taken and pre, mid and post-season for relationship between strength, explosive strength and cut performance.	3RM squat, 505-test dominant and non-dominant.	Large to very large negative correlation between relative strength and 505-test performance pre- and post (r = -0.85 to -0.6).
Emmonds et al (Emmonds *et al.*, 2017)	10 elite female soccer players.	Cross sectional study. Regression analysis of cut performance.	505-test time, change of direction deficit, isometric leg extension peak force.	Regression analyses (with strength as one of 10 variables) were able to explain 99% of the variance of the 505-test and change of direction deficit.
Peterson et al (Peterson, Alvar and Rhea, 2006)	36 female and 19 male college athletes.	Cross sectional study. Correlation between maximal strength and jumping and cut performance.	1RM back squat T-test.	Very large negative correlation between strength and T-test performance (r = -0.78).

Spiteri et al (Spiteri *et al.*, 2013)	12 stronger (8 male and 4 female) 12 weaker (4 male and 8 female) recreational team-sport athletes.	Cross sectional. Split into a stronger and weaker group using isometric strength scores.	Unilateral isometric back squat and 45° cuts.	Moderate effect for stronger athletes to be faster and show faster post stride velocity during the 45° cut (ES = 0.61 to 0.67 using Cohen's *d*).
Spiteri et al 2014 (Spiteri *et al.*, 2014)	12 elite female basketballers.	Cross sectional study. Correlation strength measures and cut performance.	1RM back squat, IMTP, 505-test, T-test, 45° reactive agility test. Eccentric and concentric back squat tests.	Very large negative correlations between strength and T-Test performance (r = -0.9 to -0.8). Very large negative correlations between strength and T-Test performance (r = -0.9 to -0.8). No significant correlation between strength and 45° reactive agility.
Swinton et al 2014 (Swinton *et al.*, 2014)	30 well trained non-professional rugby players.	Cross sectional study. Regression analysis of sprinting, jumping and cutting.	505-test, 1RM deadlift and squat.	Very large negative correlations between relative strength and 505-test (r = -0.7). Regression analysis showed relative strength measures were best predictors of 505-test performance (r^2 = 0.51 to 0.56).

Thomas et al 2015 (C Thomas *et al.*, 2015)	14 male collegiate athletes.	Cross sectional study. Correlation between IMTP and cut performance.	IMTP and 505-test.	Large negative correlation between strength and 505-test performance (r = -0.57).
Thomas et al (Thomas, Dos'Santos, *et al.*, 2016)	18 male academy cricketers.	Cross sectional study. Correlation between IMTP and cut performance.	Bilateral and unilateral IMTP, 505-test and modified 505-test.	Moderate to large negative correlations were found between strength and 505-test performance (r = -0.65 to -0.47).
Wisloff et al 2004 (Wisløff *et al.*, 2004)	17 international soccer players.	Cross sectional study. Correlation between strength and physical performance measures.	1RM half squat and 10m shuttle.	Large negative correlation between strength and 10m shuttle performance (r = -0.68).
Chaouachi et al (Chaouachi *et al.*, 2012)	23 elite male soccer players.	Cross sectional study. Regression analysis of cut performance.	T-test, 5-5-test, isokinetic concentric and eccentric leg extension and flexion strength.	Strength formed part of 8 step regression explaining 65% of the variance in the T-test performance and part of a 10-step model explaining 72% of the variance of the 5-5-test.
Young et al 2015 (Young, Miller and	24 community AFL athletes.	Cross sectional study. Correlations between physical qualities and cut performance.	1RM half squat, 45° planned and reactive cut.	No significant correlation between cutting performance and relative strength. No correlations between

Talpey, 2015)				unplanned cut and physical qualities.
Markovic 2007 (Markovic, 2007)	76 physical education students.	Cross sectional study. Correlation between strength, explosive strength and cut performance.	Lateral shuffle, 20yd shuttle and slalom run, 1RM smith machine squat, isometric squat, max single-leg squats.	No correlations between any of the strength tests and any of the cutting tests used.
Chaouachi et al 2009 (Chaouachi *et al.*, 2009)	14 Tunisian national basketball players, professional, starters.	Cross sectional study. Correlation between strength and cut performance.	1RM squat and T-test.	No correlation between squat 1RM and T-Test.

Greyed out rows are studies that found no significant relationship between strength and cutting performance. CMJ - countermovement jump, RM - repetition maximum, SJ – squat

2.2 Explosive strength - rate of force development

The ability to produce a large amount of force rapidly has been suggested to be an important quality that requires restoring during rehabilitation (Pua *et al.*, 2017) and for enhanced performance in a number of athletic tasks (Hernández-Davó and Sabido, 2014). These athletic tasks include maximum velocity sprinting (Clark, Ryan and Weyand, 2014), linear acceleration (Kawamori, Nosaka and Newton, 2013) and cutting (Spiteri *et al.*, 2017). This ability to produce a large amount of force rapidly, which will hereto be referred to as the neuromuscular quality of explosive strength, is measured using a variety of tasks from which a range of variables can be obtained. These variables can be broadly considered in terms of the production of force during execution of the task (e.g. rate of force development, power and impulse), and the overall task outcome measures (e.g. jump height or distance). Overall outcome measures have been extensively investigated within the literature and rely, to varying extents, on the force/kinetic measures which are much less commonly measured. The next four sections will review key neuromuscular explosive strength variables (rate of force development, power and impulse), and their relationship to rehabilitation and cutting performance, and the tasks commonly used to measure them, in an effort to determine the relevance of targeted neuromuscular training interventions.

2.2.1 Overview of rate of force development

Rate of force development (RFD) is the calculation of the slope of the force-time curve under isometric or dynamic conditions (Aagaard *et al.*, 2002) and has been suggested to be an important factor in sport performance (Andersen *et al.*, 2010). This is in part due to the relatively short time periods observed for force production during sporting actions. Examples of these include ground contact times during sprinting of approximately 100ms (Beneke and Taylor, 2010) and of 150ms to 350ms during cutting tasks (de Hoyo *et al.*, 2016; Dos'Santos *et al.*, 2016). These time periods should be considered with respect to the measurement of strength, particularly given maximum force is achieved at times greater than 250ms (Kawamori *et al.*, 2006). To place this in context, the athlete who is able to produce the greatest impulse in the shortest period of time rather than the athlete who can produce the most force is often at an advantage against their rivals. This is highlighted in Figure 2, where athlete A can produce a higher level of peak force than athlete B and could therefore be considered possessing greater maximum strength. However, athlete B is able to produce the greater force impulse in a shorter period of time through their greater rate of force development. This would equate to an enhanced performance outcome.

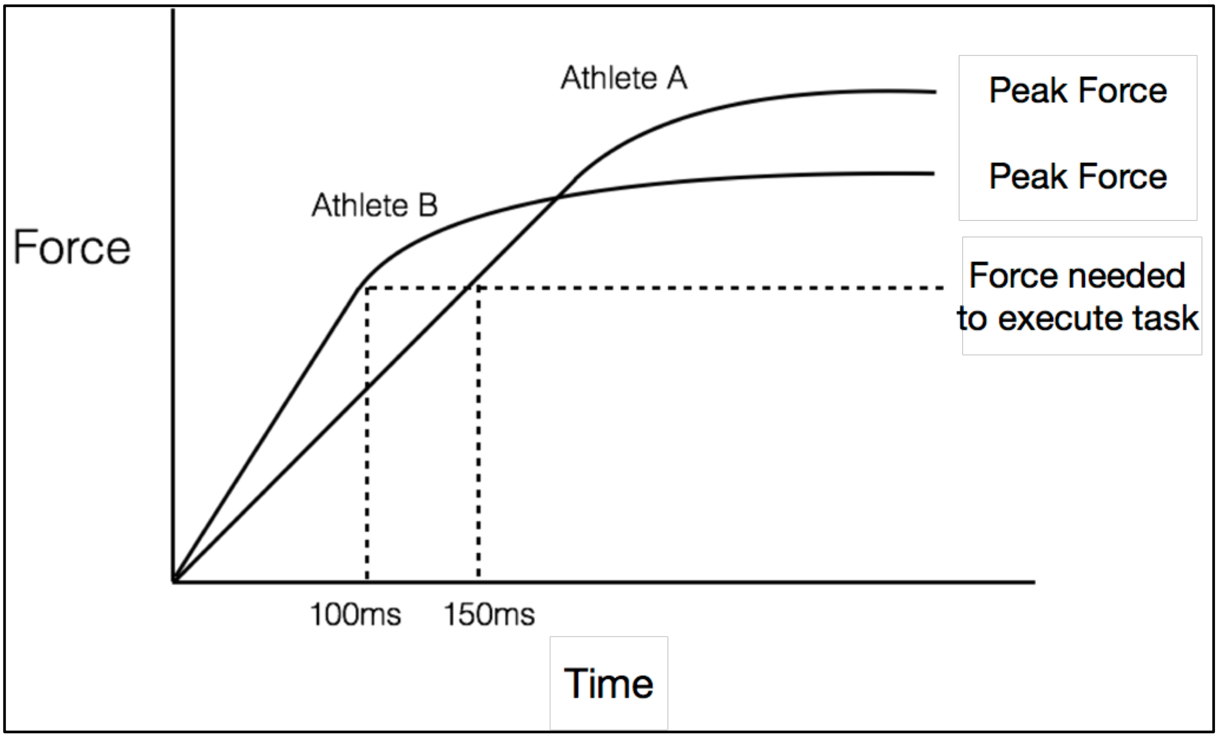


Figure 2: Force time curve showing a stronger athlete (Athlete A) with lower rate of force development compared to a weaker athlete (Athlete B)

Rate of force development has been divided into early phase (time periods less than 100ms from contraction onset) and later phase (times greater than 100ms from contraction onset) (Andersen *et al.*, 2010). Early phases of RFD have been shown to be predominantly dependent on the ability to increase muscle activation through neural factors at contraction onset (de Ruiter *et al.*, 2004). It was found that the rate of torque development during maximal voluntary isometric knee extension during the first 40ms from the onset of torque development was significantly correlated ($r = 0.87$) to the surface EMG of the knee extensors prior to initiation of torque development suggesting that high rates of torque development are dependent on the muscle pre-activation. Their findings also highlighted that voluntary rate of torque development differs between participants and can differ from induced rate of torque development (through electrically stimulated contractions). This can be observed in Figure 3 where graph A shows similar traces for induced contractions in two participants but graph B shows quite different traces for the voluntary contractions in the same two participants.

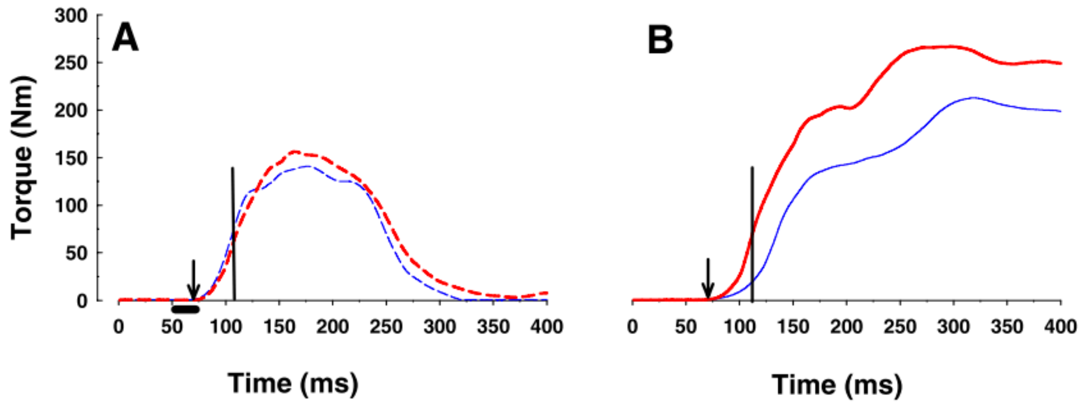


Figure 3: Graph A shows the induced contraction force traces of two participants, graph B shows the voluntary contraction force traces of the same two participants (de Ruiter *et al.*, 2004)*. The arrows indicate the initiation of torque development and the vertical lines highlight border of where initial rate of torque development ends.*

Elsewhere, Andersen & Aagaard (Andersen and Aagaard, 2006) found that a stronger relationship (*r* = 0.57) existed at early (~40ms) compared to later phases (*r* = 0.30 at 200ms) of RFD between voluntary and induced contraction RFDs. However, it was also found that as time increased, RFD was increasingly correlated with peak torque suggesting a greater dependence on the maximum strength properties of the muscle. At times greater than 150ms after the contraction onset, 80% of the variance in RFD was explained by peak torque values, whereas peak torque explained only 18-21% of the variance during the initial 40ms. Additionally, Folland et al (Folland, Buckthorpe and Hannah, 2014) investigated early and late phase RFD finding that voluntary peak force explained a greater amount of the variance (90% at 150ms) of late phase RFD compared to early phase RFD (45% at 50ms) during isometric knee extension. Early phase voluntary RFD was primarily explained (68%) by octet RFD (obtained via 8 pulses of 300Hz stimulation) corroborating the above findings that different muscle neural factors rather than maximum strength factors play a greater role during early phase RFD. It is therefore commonplace in the literature to address early and late phase RFD by measuring RFD across a number of time windows e.g. 25ms, 50ms, 75ms etc. (as seen in a summary of RFD literature Table 3 and Table 5).

While early and late phase RFD appear to have value to the practitioner given the different role of neural and maximum strength related factors and may offer some influence over rehabilitation and performance interventions, there are some factors to consider. The studies cited here used an isometric leg extension as a method of testing RFD which reduces variability in the movement by limiting the involved degrees of freedom and, from a methodological perspective, allows the use of electromyography and induced responses to investigate the role neural factors. These seated open chain movements however, offer very different challenges to the body when compared to the types of force production seen during more open athletic tasks where athletes are upright attempting to produce force through the floor utilising the whole-body. Athletic tasks also commonly involve periods of force absorption or braking prior to concentric or propulsive force production (Novacheck, 1998). Care should therefore be taken when trying to apply the above findings to these more open environments. The importance of early and late phase RFD properties during these more complex athletic tasks, in particular during cutting tasks, have received limited coverage to date and will be discussed in more detail below (section 2.2.3).

Another important consideration related to RFD in the context of both rehabilitation and athletic performance is that RFD is not a static quality. This has been demonstrated in a number of intervention studies showing interesting findings related to adaptations in early and late phase RFD. For example, Andersen et al (Andersen *et al.*, 2010) observed the effects of heavy resistance training on early and late phase RFD during a leg extension. Significant increases in late phase (>250ms) RFD were seen but not earlier throughout a leg extension movement. It was suggested that a lack of intention to accelerate the resistance as fast as possible during the 14-week training intervention was a potential reason for the lack of improvement seen in early phase RFD. The participants were instead instructed to lift in a slow and controlled manner. Of note was that early phase RFD decreased in response to training which was explained by a reduction in type IIx fibres (r = 0.61). However, increases in early phase RFD of an isometric leg press and leg extension have been observed in older adults following resistance training when emphasis was placed on explosive movements throughout the intervention (Suetta *et al.*, 2004; Caserotti *et al.*, 2008). These findings have been reproduced in younger novice populations with training focused on explosive movements proving more effective for improving RFD than more controlled movements (31% versus 17% improvement) (Young and Bilby, 1993). It is therefore possible that a lack of emphasis on how the load is lifted may reduce the effect of the training intervention on performance outcomes.

In summary, multiple studies have demonstrated greater RFD as a result of training focused on fast and forceful movements in isometric training interventions (Blazevich *et al.*, 2008; de Oliveira, Rizatto and Denadai, 2013; Oliveira *et al.*, 2015) and in multi-joint movement based interventions (Cormie, McGuigan and Newton, 2010; de Villarreal, Izquierdo and Gonzalez-Badillo, 2011; Kramer *et al.*, 2012). It has therefore been established not only that differences exist between early and late phase RFD, but that training interventions can alter both. Any analyses investigating RFD should look to distinguish between early and late phases and, if enhancement of early RFD is a primary outcome, emphasise an intention towards an explosive action during the intervention.

2.2.2 The role of rate of force development in rehabilitation

There have been limited investigations into the role of rate of force development (RFD) in rehabilitation. Fourteen studies were found investigating this area covering a wide variety of surgical procedures (anterior cruciate ligament reconstruction, total hip replacement, knee meniscectomy and total knee arthroplasty) and injuries (hamstring injury, chronic neck pain and chronic low back pain) (Table 3). This variety in populations and injuries makes it difficult to draw firm conclusions as to the role of RFD. However, ten of the fourteen studies examined differences between limbs (injured versus non-injured) or compared to control groups with all ten finding significant deficits in RFD in the injured limbs compared to the non-injured limb or compared to a non-injured control group, suggesting some relevance in RFD as a measure when considering rehabilitation.

When considering the injuries examined, of the fourteen studies found, eight studied anterior cruciate ligament (ACL) reconstructed participants. A consistent finding was that RFDs are significantly lower (20-54%) in the ACL reconstructed leg during leg extension tasks at six-months post-surgery were observed (Angelozzi *et al.*, 2012; Bie *et al.*, 2015; Jordan, Aagaard and Herzog, 2015; Kline *et al.*, 2015; Knezevic *et al.*, 2015; Blackburn *et al.*, 2016; Kadija *et al.*, 2016). Similarly in other post-surgery patients, one study investigating participants post-total knee arthroplasty observed significant deficits (sizes not reported) in knee extension RFD after six-months (Winters, Christiansen and Stevens-Lapsley, 2014). Significant deficits in RFD have also been reported in a number of other injuries/surgeries: in hamstrings of participants with previous hamstring injury (ES = 1.12-1.27) (Opar *et al.*, 2013), in quadriceps muscles five-weeks post meniscectomy surgery (24-31%) (Cobian *et al.*, 2017) and in the lumbar extensors of those with chronic low back pain compared to uninjured controls (ES = 0.93 to 1.32) (Rossi *et al.*, 2017). In addition, higher RFDs at six-weeks post-surgery were related to greater vertical jump heights (r = 0.61) at six-months (Pua *et al.*, 2017). Only two of the fourteen studies (Table 4) were intervention studies with both observing significant increases in RFD with strength interventions. The first study analysed those with chronic neck pain where significant increases in shoulder abduction RFD (61-150%) were seen in a strength intervention group but not in a general fitness or control groups (Andersen *et al.*, 2009). The second study observed increases in leg extension RFD (20-45%) in those who had undergone total hip replacement surgery following a strength training intervention while no significant changes were observed in standard rehabilitation and neuro-stimulation intervention groups (Suetta *et al.*, 2004).

While there are obvious differences in the profiles of the participants and the injuries and surgeries investigated, the finding that deficits exist in RFD in population undergoing rehabilitation from injury is consistent. Also of importance is that RFD is not a static quality in populations rehabilitating from injury and that resistance training interventions are effective in improving RFD. However, all of the interventions listed utilised tests that sought to measure single plane movements about a single joint e.g. knee extension and lumbar extension. These actions in these tests differ from those observed in sporting actions such as cutting or in activities of daily living such as sit to stand or lifting actions. There have been no studies that investigate the use of whole-body tasks to measure RFD in rehabilitating populations and so it is yet unknown whether RFD during these tasks is relevant in rehabilitation from injury.

Table 3: Studies investigating the role of rate of force development in rehabilitation.

Author	**Participants**	**Injury**	**Study design**	**Tests**	**Results**
Angelozzi et al 2012 (Angelozzi *et al.*, 2012)	45 male professional soccer players.	ACL reconstruction.	Cross sectional. Comparison to baseline measures through rehab.	Isometric unilateral leg press for RFD.	Significant (20-37%) loss of RFD from baseline measures at 6-months post op. Levels restored at 12 months.
Blackburn et al 2016 (Blackburn *et al.*, 2016)	28 females, 11 males.	Rehabilitated from ACL reconstruction min 6 months and cleared for physical activity.	Cross sectional. Between limb differences.	RTD during isometric leg extension (voluntary and evoked) and peak ground reaction force and loading rate during gait.	Significant deficits observed in RTD to peak (42%), RTD 100ms (15%), RTD 200ms (23%) and peak torque (7%) in involved side.
Kline et al 2015 (Kline *et al.*, 2015)	11 females, 10 males.	ACL reconstruction.	Cross sectional. Between limb differences in variables.	Peak torque and RTD during isometric leg extension, and 3D biomechanics during running gait.	Significantly lower RTD 100ms (69%), RTD 100-200ms (79%), RTD 200ms (76%), knee flexion excursion in stance (24%), rate of knee extensor moment (30%) in operated leg 6-months post op.

Bie et al 2015 (Bie *et al.*, 2015)	14 females, 18 males.	ACL reconstruction.	Cross sectional study. 16 ACL reconstructed (9 to 12 months post-surgery), 16 controls.	Lysholm score of knee performance, isometric knee flexion and extension peak torque and RFD over 30, 50, 100 and 200ms.	Significantly lower knee extension RFD over 30 to 100ms compared to healthy limb and control group limbs (21 to 38.8%).
Knezevic et al (Knezevic *et al.*, 2015)	20 male athletes.	ACL reconstruction.	Cohort study. Data collected 7 days pre-surgery and at 4 and 6 months post-surgery.	Isometric knee extension and flexion, peak RFD and RFD over 50, 150 and 250ms.	Significant knee extension deficits in all RFD measures (21.9 to 43%).
Kadija et al (Kadija *et al.*, 2016)	15 male athletes.	ACL reconstruction.	Cross sectional study. Data collected at 4 months post-surgery.	IKDC and Tegner questionnaires, isometric knee extension and flexion RFD over 50, 100 and 200ms.	Significant deficits in both knee flexion and extension RFDs at all time points (24 to 54%).
Winters et al 2014 (Winters, Christiansen and Stevens-	30 females, 28 males.	Total knee arthroplasty.	Cohort study. Comparison between 23 in control group and 35 post-surgery.	P RTD during isometric leg extension pre-surgery, at 1-month and at 6-months post-surgery.	Significant deficits in total knee arthroplasty participants in RTD at all time points (sizes not reported).

Lapsley, 2014)					
Jordan et al (Jordan, Aagaard and Herzog, 2015)	13 female, 16 male elite ski racers.	ACL reconstruction.	Cross sectional study. Comparison of 8 post-ACL surgery and 21 controls.	Isometric knee extension and flexion p RFD.	Significantly lower RFD at 200 and 150ms in both extension and flexion (13 to 25%).
Cobian et al 2017 (Cobian *et al.*, 2017)	10 females, 10 males.	Arthroscopic partial meniscectomy.	Cohort study. Between limb differences examined.	RTD during isometric leg extension pre-surgery, and 2-weeks and 5-weeks post-surgery.	Significant deficits in peak torque (7-16%) and RTD (24-31%) on involved side at all time points.
Opar et al 2013 (Opar *et al.*, 2013)	26 male recreational athletes.	Prior hamstring injury.	Cross sectional. Comparison between limbs 13 prior injured and 13 non-injured.	RTD and early impulse during isokinetic knee flexion.	Significantly lower RTD (ES = 1.12 to 1.27 using Cohen's *d*) for 50 and 100ms during $60 deg.sec^{-1}$ in injured limb. No significant between limb differences in uninjured limbs.
Rossi et al 2017 (Rossi *et al.*, 2017)	28 females.	Low back pain.	Cross sectional study. Comparison between 14 low	RFD during trunk flexion and extension.	Significantly lower RFD in trunk extension over 100ms and 200ms (ES = 0.93 and 0.99 using Cohen's *d*).

			back pain and 14 control.		
Friesenbichler et al 2017 (Friesenbichler *et al.*, 2017)	9 females, 12 males.	Total hip arthroplasty.	Cohort study. Comparison between limbs.	RFD during isometric knee flexion and extension, and hip flexion, abduction and adduction.	Significant deficit in knee extensor RFD (19%) between limbs pre-surgery.
Pua et al 2017 (Pua *et al.*, 2017)	10 females, 60 males.	ACL reconstruction.	Cohort study. Relationships between strength and RTD at 6 weeks and jump scores at 6 months.	RTD during isometric leg extension at 6-weeks post-op. Single-leg hop for distance and CMJ at pre-surgery and 6-months post-surgery	Significant relationship between greater RTD at 6-weeks was associated with greater jump height (1.76-2.03cm) and distances (23-27.3cm)

ACL - anterior cruciate ligament, RFD - rate of force development, RTD - rate of torque development

Table 4: Intervention studies investigating the role of rate of force development in rehabilitation.

Author	**Participants**	**Injury**	**Study design**	**Tests**	**Results**
Suetta et al 2004 (Suetta *et al.*, 2004)	36 elderly individuals.	Post hip replacement surgery.	12-week intervention. 3 groups: (i) lower body strength training, (ii) neuro-stimulation, (iii) standard rehabilitation withl hip strength and ROM training.	Maximal isometric knee extension for RFD.	Significant increase in RFD (20-45%) in 30ms, 50ms, 100ms, 200ms, no significant increases seen in standard rehab and neuro-stimulations groups.
Andersen et al 2009 (Andersen *et al.*, 2009)	42 females.	Trapezius myalgia.	10-week intervention. Three groups; (i) specific strength training, (ii) general fitness, (iii) reference.	Isometric shoulder abduction RTD.	Significant increase in RTD (61-150%).

RTD - rate of torque development, RFD - rate of force development

2.2.3 The role of rate of force development in cutting performance

The following section will show that, to date, the literature points towards a positive relationship between higher levels of rate of force development and enhanced cutting performance outcomes, but that there are a low number of studies investigating the relationship. A broader overview of the literature surrounding rate of force development variables and other tasks of athletic performance (namely jumping and sprinting), will show a similar positive link between RFD and performance and that this relationship may be impacted by the use of relative and absolute measures of force.

Only five studies were found that investigated the relationship between rate of force development (RFD) variables and cutting performance (summarised in Table 5). Of these, three studies found significant negative correlations between RFD and cutting performance outcome variables (Swinton *et al.*, 2014; Spiteri, Newton and Nimphius, 2015; Emmonds *et al.*, 2017). One study found a mixed relationship between RFD and cutting performance outcomes (Wang *et al.*, 2016). One study found no significant relationship between RFD and cutting performance outcomes (Townsend *et al.*, 2017).

Spiteri et al (Spiteri, Newton and Nimphius, 2015) found significantly greater RFD during the first 90ms (84%) and 100ms (78%) of an isometric mid-thigh pull test in faster compared to slower participants during a 45° cutting task. Swinton et al (Swinton *et al.*, 2014) found significant correlations between greater RFD normalised to peak force in a jump squat and performance outcome in the 505-test (r = -0.51). Emmonds et al (Emmonds *et al.*, 2017) performed a regression analysis using 505-test time and change of direction deficit as dependent variables with a range of strength, explosive strength and reactive strength tests as independent variables. They observed that predominantly RFD measures obtained during a leg extension strength test, a squat jump and a countermovement jump explained 99% of the variance in both the 505-test time and change of direction deficit. Wang et al (Wang *et al.*, 2016) measured T-test and pro-agility test times, isometric mid-thigh pull (IMTP) peak forces and RFDs across multiple time-points, sprint performance and 1RM squat in fifteen university rugby players. They observed significant correlations between peak and ≤100ms RFD (r = -0.53 to -0.52) and pro-agility test time. Of interest is that no significant correlations were observed between any RFD variable and T-test performance. The pro-agility test involves the athlete starting side on but immediately turning to move to face forwards during the first 5m, prior to a 180° cut to run forwards 10m prior to the final 180° and the final 5m forwards run. In contrast, the T-test involves a 10yd run prior to a series of side shuffles and a backwards run to the beginning. The T-test arguably involves a greater coordinative challenge than the pro-agility test due to the side shuffling and backwards running components and may mean that coordination in the movements rather than explosive strength qualities such as RFD were factors with greater relevance to performance outcomes. Only one study found no significant correlation between RFD and performance outcome in a cutting task. Townsend et al (Townsend *et al.*, 2017) found no significant correlations between RFD measures and pro-agility or lane agility performance outcome.

While the above studies have investigated the relationship between different RFD measures and cutting performance, none analysed rate of force development during the cutting task itself. This is necessary to understand, initially, if RFD is a measure that is important for enhanced cutting performance outcomes. Further, given the equivocal nature of the relationship between RFD and cutting performance outcome, it is necessary to understand if RFD is a task specific quality that is task specific or has a broader transfer across tasks. This has yet to be investigated in the literature.

Table 5: Studies investigating the role of rate of force development in cutting performance.

Author	**Participants**	**Study design**	**Performance tests**	**Results**
Spiteri et al 2015 (Spiteri, Newton and Nimphius, 2015)	12 professional female basketball players.	Cross sectional study. Comparison of faster and slower cutting groups.	IMTP RFD 0-30, 0-50, 0-90 and 0-100ms, 45° cut time.	Large effect for greater RFD in first 90ms and 100ms (ES = 1.5 using Cohen's *d*) in the faster cutting athletes. No difference in RFD at earlier times between groups.
Swinton et al 2014 (Swinton *et al.*, 2014)	30 non-professional rugby players.	Cross sectional study. Regression analysis of sprinting, jumping and cutting.	1RM back squat and deadlift RFD, 505-test.	Moderate to large negative correlations between RFD and 505 time (r = -0.5 to -0.38).
Emmonds et al (Emmonds *et al.*, 2017)	10 elite female soccer players.	Cross sectional study. Regression analysis of cut performance.	505-test time, change of direction deficit, SJ and CMJ propulsive RFD.	Regression analyses explained 99% of the variance (of which RFD were 3 of 7 variables) of the 505-test and change of direction deficit

Wang et al 2016 (Wang *et al.*, 2016)	15 male university rugby players.	Cross sectional study. Correlation between IMTP variables and cut performance.	IMTP peak RFD and RFD over the first 30, 50, 90, 100, 150, 200 and 250ms, pro-agility test, T-test.	Large negative correlations between peak and ≤100ms RFD (r = -0.53 to -0.52) and pro-agility test time. No significant correlations between any RFD measures and T-test performance were observed.
Townsend et al 2017 (Townsend *et al.*, 2017)	15 female, 8 male college basketball players.	Cross sectional study. Correlation between IMTP variables and cut performance.	IMTP peak RFD and RFD over the first 50, 100, 150, 200, 250ms, pro-agility test and lane agility test.	No significant correlations between RFD measures and cutting tasks or peak force.

IMTP - isometric mid-thigh pull, RFD - rate of force development, RTD - rate of torque development, RM - repetition maximum. Greyed out rows highlight studies no significant correlations observed between RFD and cutting performance measures

2.2.4 The role of rate of force development in athletic performance and maximum strength

Given the relatively low number of studies investigating the role of rate of force development (RFD) in cutting performance, the relationship with broader tasks of athletic performance, namely jumping and sprinting (summarised in Table 6), will now also be reviewed.

The vertical jump is an athletic task where the relationship with RFD has been well investigated. However, only five studies have considered the relationship when RFD is measured within the jumping task itself (Floria and Harrison, 2013; Laffaye and Wagner, 2014; Marques *et al.*, 2015; Jiménez-Reyes *et al.*, 2016; Barker, Harry and Mercer, 2018). A more common approach has been to obtain rate of force development with other tasks such as the isometric mid-thigh pull. Some variety exists in the selection of RFD variables used for example peak RFD and mean RFD across different time-points. Regardless of the measure used, it appears a consistent finding that a correlation exists between jump height and RFD. Of the twenty studies found looking at the relationship between RFD (measured both within the jump itself and within other tasks) and jump height, fifteen showed significant moderate to strong correlations (r = 0.33 to 0.86) (Paasuke, Ereline and Gapeyeva, 2001; De Ruiter *et al.*, 2006; de Ruiter *et al.*, 2007; Kraska *et al.*, 2009; West *et al.*, 2011; McLellan, Lovell and Gass, 2011; Tillin, Pain and Folland, 2012; Muehlbauer, Gollhofer and Granacher, 2012; Thompson *et al.*, 2013; Ćopić *et al.*, 2014; Marques *et al.*, 2014; Chang *et al.*, 2015).

Of note is that Thompson et al (Thompson *et al.*, 2013) found no correlations between absolute variables of RTD and jump height, but did find a correlation with relative RTD. In fact, all six of the studies using relative RFD (i.e. relative to body-mass) found significant correlations with jump height. The relationship with absolute values is less clear. Of the fourteen studies investigating vertical jump height and absolute RFD measures, eight found significant correlations whilst six found no significant relationship. It would appear therefore that the use of relative and absolute measures impacts the relationship between RFD and vertical jump height.

The relationship between RFD measures and sprinting performance shows a similar pattern to that of the jumps although the literature is limited. Of the five studies investigating the relationship, the two studies that used relative RFD measures (West *et al.*, 2011; Tillin, Pain and Folland, 2012) found a significant correlation with sprinting performance (ES = 0.41 to 0.43; r = -0.68 to -0.66). The three studies that utilised absolute measures found no correlations (Wilson *et al.*, 1995; Marques *et al.*, 2011; Marques and Izquierdo, 2014). Of the five studies found, the distances measured as sprint performance were between 5m and 30m in distance, and as such are more measures of acceleration as it takes 30-50m to reach maximum velocity in sprinting (Krzysztof and Mero, 2013). Given one of the primary objectives in acceleration during running from stationary and jumping is to overcome inertia, it follows that body-mass would play a role in an athlete's ability to perform these tasks. It would therefore appear from the above evidence that relative RFD is a more relevant measure than absolute RFD in when investigating the relationship with athletic performance.

Of the six studies examined in the previous section (2.2.3) investigating the relationship between RFD and cutting performance, only two studies considered RFD relative to body-mass (Spiteri, Newton and Nimphius, 2015; Cronin *et al.*, 2016). In a field sport context, lower body-mass has also been shown to be a factor in enhanced cutting performance (Spiteri, Newton and Nimphius, 2015). Given the apparent difference between the use of absolute and relative measures of RFD in jumping and sprinting, consideration should therefore be given to the use of absolute and relative measures of RFD when examining cutting performance.

A final consideration regarding RFD is the relationship that exists with maximum strength, particularly given the relationship between later phases of RFD and peak force production during single joint tasks discussed above (2.2.1). Twelve studies were found that investigated the relationship between maximum strength and RFD (Table 7). Nine out of the twelve studies demonstrate significant correlations between RFD and maximum strength (r = 0.42 to 0.93). All three of the studies that found no significant correlation (Haff *et al.*, 2005; McGuigan, Winchester and Erickson, 2006; McGuigan and Winchester, 2008) used maximum or peak RFD measures during the isometric mid-thigh pull to compare with peak force. Of the nine that demonstrate a relationship between RFD and maximum strength, six measured RFD across different time points rather than a peak value. This might suggest that the way RFD is calculated has a bearing on the relationship with maximum strength. Peak RFD gives the greatest value from multiple small portions of the force-time curve. Windows of 2-50ms have been used in the literature with 20ms windows suggested to optimise reliability (Haff *et al.*, 2014). However, these portions may include the periods of fluctuation of force that occur during isometric movements as the athlete attempts maximum force production over an extended period of time. An example of this is seen in Figure 4. This is a consideration when using RFD as a measure and highlights the necessity behind understanding the patterns of force production observed during tasks. The use of time windows rather than peak RFD measures may allow a greater understanding of the roles of early and late phase RFD. However, care should be taken when using RFD as a sole measure of explosive strength, due to the fluctuations in force production observed in athletic tasks.

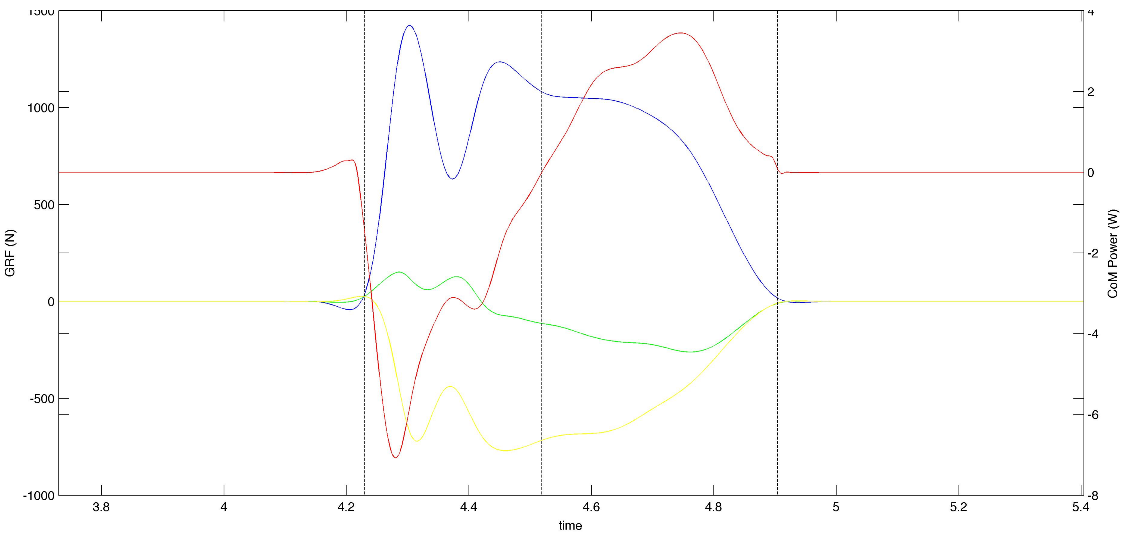


Figure 4 Force Time Curves of a 110° cut. Blue - vertical ground reaction force, yellow - vertical ground reaction force, green - anterior ground reaction force, red - centre of mass power

2.2.5 Conclusion

Rate of force development appears a relevant measure when considering rehabilitation from injury due to the consistency in deficits observed in injured populations. It also is relevant when considering tasks of athletic performance although consideration of the use of absolute and relative measures is necessary. There is currently no literature that has investigate RFD measures in whole-body actions in rehabilitating populations which is in contrast to work around performance. In addition, specifically for cutting performance, there are no studies that have analysed RFD measures during the cutting task itself and, more broadly, only five studies have investigated the relationship with RFD. Further work is therefore needed to broaden the understanding around the relationship between cutting and RFD.

Table 6: Studies investigating the role of rate of force development in jumping and sprinting (RFD not assessed during jumping and sprinting)

Author	**Participants**	**Relationship w/**	**Study design**	**Performance tests**	**Results**
Floria et al (Floria and Harrison, 2013)	36 female gymnasts	Jumping	Cross sectional study	CMJ	Moderate effect for the difference between higher and lower jumpers for greater eccentric RFD (ES >0.9) and lower concentric RFD)
Laffaye & Wagner (Laffaye and Wagner, 2014)	178 males	Jumping	Cross sectional study	CMJ	Significant moderate correlation between eccentric RFD and CMJ jump height (r = 0.50)
Marques et al (Marques *et al.*, 2015)	35 trained males	Jumping	Cross sectional study	CMJ	Large positive correlations between peak RFD and RFD at peak force in the CMJ and CMJ jump height (r = 0.77 to 0.81)
Barker2018 (Barker, Harry and Mercer, 2018)	26 male soccer players	Jumping	Cross sectional study	CMJ	No significant correlations between absolute eccentric RFD and CMJ jump height

Jimenez-Reyes et al (Jiménez-Reyes *et al.*, 2016)	32 trained males	Jumping	Cross sectional study	Loaded squat jump	No significant effects of absolute RFD measures on jump height
Chang et al 2015 (Chang *et al.*, 2015)	30 recreationally active (15 male, 15 females)	Jumping	Cross sectional study	Isometric hip and knee extension and ankle plantarflexion RTD, CMJ	Large positive correlations between RTD about the knee and ankle and CMJ height (r = 0.53 to 0.57). No correlation with RTD about the hip
Copic et al 2014 (Ćopić *et al.*, 2014)	35 elite female volleyball athletes, 21 active females	Jumping	Cross sectional study	CMJ height with and without arm swing, isometric leg-press absolute and relative, peak RFD and RFD over 200ms.	Moderate to large positive correlations between RFD and CMJ height (r = 0.33 to 0.64).
De Ruiter et al 2006 (De Ruiter *et al.*, 2006)	9 untrained males	Jumping	Cross sectional study	Voluntary and evoked isometric leg extension RTD, SJ and CMJ heights at 90° and 120° knee flexion	Very large correlations between RTD and SJ and CMJ heights at both 90° and 120° (r = 0.75 to 0.86). No significant correlation between RTD

					over 100ms and jump height.
De Ruiter et al 2007 (de Ruiter *et al.*, 2007)	11 elite male volleyball players	Jumping	Cross sectional study	Voluntary and evoked isometric leg extension RTD, time to peak RTD, torque time integral, SJ and CMJ heights at 90° and 120° knee flexion	Large to very large positive correlation between evoked RTD and SJ and CMJ (r = 0.59 to 0.84). No significant correlation between voluntary RTD and jump heights.
Kawamori et al 2006 (Kawamori *et al.*, 2006)	8 male weightlifters	Jumping	Cross sectional study	IMTP peak RFD, time to peak RFD, CMJ and SJ peak force, peak RFD, time to peak RFD, height and PP. Hang pull at 120%, 90%, 60% and 30% or 1RM hang clean, peak RFD, time to peak RFD	No significant relationship between absolute peak RFD and CMJ or SJ.
Kraska et al 2009 (Kraska *et al.*, 2009)	41 females, 21 males	Jumping	Cross sectional study	SJ height (0kg and 20kg), CMJ height (0kg and 20kg), IMTP peak RFD, RFD at 50, 90, 250ms.	Moderate to large positive correlations between IMTP relative RFD and CMJ and

					SJ heights (r = 0.43 and 0.66).
Marques et al 2014 (Marques *et al.*, 2014)	35 males	Jumping	Cross sectional study	Smith machine CMJ RFD, power, force, displacement and time variables	Very large positive correlations between absolute peak RFD and jump height (r = 0.83).
McGuigan et al 2006 (McGuigan, Winchester and Erickson, 2006)	8 College Wrestlers	Jumping	Cross sectional study	IMTP RFD, VJ height	No significant correlation between absolute RFD measures and jump performance.
McGuigan et al 2008 (McGuigan and Winchester, 2008)	22 male college american footballers	Jumping	Cross sectional study	IMTP peak RFD, VJ height and broad jump distance	No significant correlation between absolute RFD measures and jump performance.
McLellan et al 2011 (McLellan, Lovell and Gass, 2011)	23 physically active but non-resistance trained men	Jumping	Cross sectional study	CMJ and SJ height, peak RFD, average RFD	Moderate to large positive correlations between absolute peak RFD and CMJ displacement a (r = 0.49 to 0.68).

Muehlbauer et al 2012 (Muehlbauer, Gollhofer and Granacher, 2012)	18 males, 19 females	Jumping	Cross sectional study	CMJ power and height, isometric plantar flexion RTD.	Large positive correlations between absolute RTD and CMJ height (r = 0.63). Regression anlysis showed significance between RTD and CMJ height (r = 0.69).
Nuzzo et al 2008 (Nuzzo *et al.*, 2008)	12 male college athletes	Jumping	Cross sectional study	CMJ jump height, IMTP and isometric squat RFD	No significant correlation between RFD measures and jump height or jump velocity.
Paasuke et al 2001 (Paasuke, Ereline and Gapeyeva, 2001)	9 male nordic combined athletes and 12 untrained males	Jumping	Cross sectional study. Comparison of controls and untrained athletes	Isometric knee extension peak RFD, SJ height, CMJ height	Large to very large positive correlations between absolute RFD and jump heights (r = 0.62 to 0.83).
Thompson et al 2013 (Thompson *et al.*, 2013)	31 male NCAA football players	Jumping	Cross sectional study	Isometric leg extension and flexion (RTD 0-30, 0-50, 0-100, 0-200ms), CMJ height	Moderate to very large positive correlations between relative RTD measures and jump height (r = 0.4 to 0.72). No

					significant correlation when absolute values used.
Marques 2014 (Marques and Izquierdo, 2014)	32 trained males	Sprinting	Cross sectional study	Smith machine CMJ RFD, 10m sprint	No significant correlation between absolute RFD in CMJ and 10m sprint.
Marques et al 2011 (Marques *et al.*, 2011)	25 male amateur field sports athletes	Sprinting	Cross sectional study	5m sprint time, smith machine CMJ RFD	No correlations between peak absolute RFD and 5m sprint times.
Tillin et al 2012 (Tillin, Pain and Folland, 2012)	18 male rugby union players and 8 untrained males	Sprinting	Cross sectional study. Comparison of rugby players and untrained groups	Isometric squat peak force and force at 50, 100, 150, 200 and 250ms, isometric explosive squat, 5m and 20m sprint	Small significant effects observed for faster athletes showing greater RFD (+ 49 to 62%, ES = 0.41 to 0.43 using Cohen's *d*). Normalised force was 33-67% greater at 50, 100 and 150ms among the faster athletes.
Wilson et al (Wilson *et al.*, 1995)	15 males	Sprinting	Cross sectional study	Smith machine isometric squat, SJ and CMJ peak force, peak RFD and	No correlation between absolute RFD measures and sprint performance

				impulse 100ms, 30m sprint time	
West et al 2011 (West *et al.*, 2011)	39 male professional rugby league players	Sprinting and jumping	Cross sectional study	IMTP absolute peak and relative peak force and peak RFD, 10m sprint time	Large negative correlation between peak RFD and 10m sprint time (r = -0.66)

CMJ - countermovement jump, IMTP - isometric mid-thigh pull, RFD - rate of force development, SJ - squat jump, ES - effect size, RTD - rate of torque development, VJ - vertical jump, RM - repetition maximum.

Table 7: Studies investigating the relationships between maximum strength and rate of force development.

Author	**Participants**	**Study design**	**Performance tests**	**Results**
Andersen et al 2010 (Andersen *et al.*, 2010)	15 males in resistance training group, 10 in control group matched for age height and weight. None regularly participated in exercise	Intervention study. 14 weeks, 3 sessions a week, 4-5 sets of lower body exercises. Progressing in intensity 10-12RM, 8-10RM, 6-8RM.	Isometric knee extension peak torque, RFD 0-10, 0-20, 0-30…0-250ms and RFDr (normalised to MVC). Muscle biopsies VL,	RFD increased 11% at 250ms, no change at earlier times. RFDr reduced 10-18% across 0-140ms which was correlated with negative change in % type IIX fibres. MVC increase 18% in training group but no change in control group.
Bazyler et al 2015 (Bazyler, Beckham and Sato, 2015)	17 recreationally-trained college-age males	Cross sectional study	1RM back squat, 1RM partial squat, IS 90° knee angle, IS 120° knee angle, IRFD 0–250ms with Iso Squat at 90° and 120°	Significant correlation between IS PF at 90° and RFD at 90° (r = 0.68), RFD at 120° (r = 0.44), between ISPF at 120° and RFD at 90° (r = 0.39), RFD at 120° (r = 0.64), between 1RM back squat and RFD at 90° (r = 0.55), RFD at 120° (r = 0.43)

Beckham et al (Beckham *et al.*, 2013)	12 male and 2 female intermediate to advanced weightlifters	Cross sectional study	IMTP, RFD (0–100, 0–150, 0–200, 0–250ms)	Significant correlation between peak force and RFD (*r* = 0.73) (0–250ms) with no significant correlation at 0–100ms (r = 0.34), 0=150ms (*r* = 0.42), 0–200ms (*r* = 0.56)
Kawamori et al 2006 (Kawamori *et al.*, 2006)	8 college weightlifters	Cross sectional study	Dynamic clean pull 30, 60, 90, 120% 1RM, IMTP, PF, RFD, CMJ, SJ	Strong correlations between IMTP PF and CMJ PF (*r* = 0.87), PRFD (*r* = 0.85), PP (*r* = 0.95) and displacement (*r* = 0.82). Strong correlation between IMTP PF and SJ displacement (*r* = 0.87). No significant correlation between PRFD and CMJ or SJ.
Kawamori et al 2005 (Kawamori *et al.*, 2005)	15 collegiate male athletes	Cross sectional study	1RM hang clean, 30,40,50,60,70,80,90% 1RM power and peak RFD in hang clean	Significant correlations between PF in 1RM hang clean and peak RFD in CMJ (*r* = 0.53) and SJ (*r* = 0.68)

Kraska et al 2009 (Kraska *et al.*, 2009)	41 female and 22 male NCAA div 1 field and court sport athletes	Cross sectional study	SJ, CMJ, IMTP collected PF, RFD, Force at 50, 90, 250ms. Athletes were also grouped as weak and strong for analysis	Strong correlation between PF and RFD (r = 0.88), F50 (r = 0.85), F90 (r = 0.42), F250 (r = 0.93). Moderate correlations between SJ and PF (r = 0.4), RFD (r = 0.49) and CMJ and PF (r = 0.36), RFD (r = 0.43). Significant diff in SJ and CMJ height decrease (diff between unloaded and 20kg loaded), RFD and PF 50, 90 and 250. No difference in SJ and CMJ height though
Stone et al 2004 (Stone *et al.*, 2004)	15 male local cyclists and 15 male national and international cyclists	Cross sectional study	IMTP PF and peak RFD, CMJ, SJ, cycling power and 1 lap time trial	Significant correlation between PF and peak RFD on each test day (r = 0.46 and 0.68) (not when normalised to bodymass), and between peak force and ranking on each test day (r = 0.68 and 0.7)
Thomas et al 2015 (Thomas et al. 2015)	22 male college athletes	Cross sectional study	SJ height, CMJ height, IMTP PF, peak RFD, impulse at 100, 200 and 300ms and total impulse	Significant correlation between absolute and relative PF and PRFD (r= 0.7). No significant correlation between PF or peak RFD and CMJ and SJ performance however there is

				with CMJ PF (*r* = 0.45) and SJ PP (*r* = 0.46)
Zaras et al 2016 (Zaras *et al.*, 2016)	6 male and 6 female competitive throwers	Intervention study. 2x5 week blocks. Block one hypertrophy and max strength focus, block 2 max strength and power. 3-4 gym sessions per week, 2-3 throwing sessions per week	Shotput, javelin, hammer, Isometric leg press PF and RFD at 50, 100, 150, 200 and 250ms, 1RM leg press, hang power clean and back squat	Significant correlation between PF and RFD at 100, 150, 200 and 250ms pre (*r* = 0.59, 0.72, 0.73, 0.74) and post training (*r* = 0.721, 0.83, 0.86, 0.90).
McGuigan & Winchester 2008	22 male college footballers	Cross sectional study	1RM back squat, bench press and power clean, 2RM	No significant correlations with RFD measure. Significant correlations

(McGuigan and Winchester, 2008)			split jerk, IMTP PF and RFD, VJ, broad jump	between PF and 1RMs (*r* = 0.61 to 0.72) and 2RM split jerk (*r* = 0.57).
McGuigan et al 2006 (McGuigan, Winchester and Erickson, 2006)	8 male college wrestlers	Cross sectional study	1RM back squat and power clean, IMTP PF and RFD, VJ	No significant correlations with RFD measure. Significant correlation between PF and squat 1RM (*r* = 0.96 and power clean *r* = 0.97).
Haff et al 2005 (Haff *et al.*, 2005)	6 elite female weightlifters	Cross sectional study	1RM snatch and clean and jerk, IMTP PF and peak RFD, IMTP at 30kg, MTP at 100kg, CMJ, VJ	No significant correlation between IMTP PF measures and RFD at submaximal mid-thigh pulls. Significant correlation between IMTP PRFD and combined snatch and clean and jerk (*r* = 0.8)

Greyed out rows show no significant correlations between strength and rate of force development. SJ - squat jump, CMJ - countermovement jump, VJ - vertical jump, RM - repetition maximum, IS - isometric squat, RFD - peak rate of force development, MVC - maximum voluntary contraction, IMTP - isometric mid-thigh pull, PF - peak force, PP - peak power

2.3 Explosive strength - power

This section will examine power as a variable and its relationship with both rehabilitation and cutting performance. There is a larger body of literature using power as a variable and its relationship with rehabilitation than there is to cutting performance. This section will show that, within rehabilitation, deficits in power are consistently observed in those rehabilitating from multiple musculoskeletal injuries and that the relationship between power and cutting performance appears to be inconsistent.

2.3.1 Overview of power

Power is the rate at which work is done in moving an object, in this instance, vertically. It is calculated as:

$$Power = \frac{W}{t} = \frac{F.d}{t} = F.v$$

where *W* is the work done, *t* is the time over which work (force) is done, *F* is the force applied to the body, *d* is the distance over which force is applied to the object and *v* is the velocity of the body. The calculation of power using a kinetic only approach with force platform ground reaction force data was described by Harman et al (Harman *et al.*, 1991) whereby the vertical force produced during a jump was considered to act upon the centre of mass. In which case, the vertical velocity of the centre of mass was derived from the impulse momentum relationship:

$$\Delta v = \frac{F.t}{m}$$

where *v* is the instantaneous velocity, *F* is the vertical ground reaction force minus the bodyweight, *t* is the time over which force is applied and *m* is the mass of the body. Power can also be calculated using a kinematic only approach through displacement-time graphs which can be generated using multiple methods for example by using a linear position transducer (Baker, Nance and Moore, 2001).

This displacement-time data can be differentiated firstly to generate velocity-time data:

$$v = \frac{\Delta d}{\Delta t}$$

where *v* is the instantaneous velocity of the object, *d* is the displacement of the object and *t* is time over which displacement is considered. Velocity is then differentiated again to produce acceleration-time data:

$$a = \frac{\Delta v}{\Delta t}$$

where *a* is the acceleration of the object, *v* is the velocity of the object and *t* is the time over which the velocity is considered. This is then multiplied by the system mass to produce force-time data which is multiplied by the velocity time data to give power:

$$F = ma$$

$$Power = F.v$$

Interpretations of the calculation of power should be considered in context to potential issues with validity with both kinetic an kinematic only approaches (Cormie, Deane and McBride, 2007). It was observed in this instance that the kinetic only force plate approach underrepresents velocity and hence power output, and the double differentiation used in the calculation during the kinematic only approach, can amplify noise leading to inaccuracies. Cormie et al (Cormie, Deane and McBride, 2007) suggest using a combination of both kinetic and kinematic approaches to obtain the most valid measure. Using a combination of kinematic and kinetic measures, can be achieved through the use of 3D biomechanical analysis. This method allows the calculation of centre of mass power in all planes but also about individual joints. Of further note when considering power as a variable is that, given power is calculated with the use of displacement and or velocity, it is only a measurable quality during dynamic tasks.

2.3.2 The role of power in rehabilitation

When considering the role of power as a measure in rehabilitation, the majority of the literature is focused about the knee (Table 8) and, in particular, rehabilitation from anterior cruciate ligament (ACL) reconstruction. This is likely due, firstly, to the variable being relatively easy to measure about the knee using an isokinetic dynamometer for knee extension, knee flexion or leg press movements. Secondly, many of those rehabilitating from ACL reconstruction are aiming for sporting return to play and it is possible power is seen as a more relevant variable in this population as opposed to those simply returning to activities of daily living. Fifteen studies were found with three broad findings across them. Nine studies demonstrated between limb deficits (8 to 38.5%) in power in the injured limb (Pincivero, Heller and Hou, 2002; Orishimo *et al.*, 2010; Castanharo *et al.*, 2011; Thomee *et al.*, 2012; Di Stasi *et al.*, 2013; Ageberg and Roos, 2016; Chimenti *et al.*, 2016; Bodkin *et al.*, 2017; Pratt and Sigward, 2017). Three other studies observed a relationship between greater asymmetries in power and poorer outcome measures (r = 0.28 to 0.53) (Ageberg and Roos, 2016; Chimenti *et al.*, 2016; Bodkin *et al.*, 2017). Finally, three studies demonstrated that power is a trainable quality in those rehabilitating from injury (Barker *et al.*, 2012; Kristensen and Burgess, 2013; Bieler *et al.*, 2014).

The most common tested injury was among ACL reconstructed patients where deficits in power compared to non-operated limbs were observed from 6 to 24 months post-ACL surgery in a range of tasks (Pincivero, Heller and Hou, 2002; Orishimo *et al.*, 2010; Castanharo *et al.*, 2011; Thomee *et al.*, 2012; Di Stasi *et al.*, 2013; Bodkin *et al.*, 2017; Pratt and Sigward, 2017) and significant correlations were observed between larger asymmetries in power and poorer Knee Injury and Osteoarthritis Outcome Scores (KOOS) (Ageberg and Roos, 2016; Bodkin *et al.*, 2017). In other conditions, power has been shown to be a relevant variable to understand medial joint loading in those with knee osteoarthritis (Calder *et al.*, 2014) and for deficits to be observed in ankle power in those with Achilles tendinopathy (Chimenti *et al.*, 2016). Another observation within the literature is that power is a trainable quality among injured populations. Bieler et al (Bieler *et al.*, 2014) found this in an ACL injured population with those adopting a high intensity training program compared to those following a low intensity program demonstrating a significantly greater increase in knee extension power (13 to 14%). Power has also been shown to be a relevant and trainable measure in other injuries, where leg extension power has shown to be restored 1 year following knee replacement surgery (Barker *et al.*, 2012) and has been found to increase with higher intensity interventions demonstrating greater increases in power across a broad range of musculoskeletal conditions (effect sizes not reported) (Kristensen and Burgess, 2013). However, this has not been seen in all injuries (Biernat *et al.*, 2013; Hu *et al.*, 2017) for example, lumbar extension power has been found to have no significant correlation with low back pain and disability (Hu *et al.*, 2017). While power has been considered with respect to a large variety of injuries, it has yet to be measured as a variable in those with athletic groin pain. Broadly though, power appears to be a quality where deficits can remain over a long period of time in those rehabilitating from lower limb injury with links to poorer scores in outcome measures observed, but is a changeable quality with training interventions. Despite differences between limbs and between injured and non-injured populations being observed, it's relevance as a quality for returning from groin injury requires further investigation.

Table 8: Studies investigating the role of power in rehabilitation.

Author	Participants	Injury	Study design	Tests	Results
Pincivero et al 2002 (Pincivero, Heller and Hou, 2002)	12 females, 11 males. 10 healthy, 7 ACL deficient, 6 ACL reconstructed.	ACL rupture.	Cross sectional study. All participants 26-64-months post-surgery.	Isokinetic knee extension and flexion at 1.05 and 3.14 rad.s^{-1} average power.	Significantly lower quadriceps average power in ACL reconstructed average power (12-13%) compared to ACL deficient knee.
Bodkin et al 2017 (Bodkin *et al.*, 2017)	36 females, 15 males. 17 early (9mths-2 years) post-surgery, 17 middle (2-5 years) post-surgery, 17 late (5-15 years) post-surgery.	ACL reconstruction.	Cross sectional study. Comparison of 3 different time-points post-surgery.	Isokinetic knee extension and flexion average power.	Moderate positive correlation between lower knee flexion power poorer knee outcome scores (r = 0.30 to 0.38). Significantly lower knee extension power in early compared to both groups (12%).
Calder et al 2014 (Calder *et al.*, 2014)	42 female, 11 male 40-70 year olds.	Knee osteoarthritis.	Cross sectional study. Correlation with knee adduction moments during gait.	Isokinetic knee extension peak power.	Knee extension power explained 8.2% of variance in knee adduction moment and 6.8% of the variance in knee adduction moment impulse.

Biernat et al (Biernat *et al.*, 2013)	28 male 16 to 19 year old volleyball players. 15 in experimental group, 13 in control.	Patellar tendinopathy.	Intervention study. 24 weeks of strength training including decline squats. Control group undisclosed, assumed normal training.	Peak power during CMJ, VISA-P questionnaire.	No significant difference between experimental and control groups in peak power at the end of 24-week intervention even with significant difference in pain reduction compared to control group.
Kristensen & Burgess (Kristensen and Burgess, 2013)	27 male soldiers. 13 in functional strength group, 13 in normal rehab.	Mixed MSK conditions.	Intervention study. 3 weeks of functional strength training involving heavier loading than the normal rehab group.	Power measured using CMJ.	Significant increases in power and strength in both groups (values not reported) with greater, but not significant increases in the functional training group observed.
Barker et al (Barker *et al.*, 2012)	23 females, 21 males.	Unilateral knee replacement.	Cohort study. Participants measured pre-surgery, at 1-year and 2-year post-surgery.	Leg extension power, Oxford knee score, Tegner activity score.	Leg extensor power restored at 1 year following surgery with smaller further increase at 2 years.

Bieler et al (Bieler *et al.*, 2014)	19 females, 31 males. 25 in high intensity group, 25 in low intensity group.	ACL reconstruction.	20-week intervention study starting 8-weeks post-surgery. High intensity group (20RM to 8RM), low intensity group (30RM to 20RM).	Unilateral leg press power.	Significantly greater knee extension power at 14 weeks (13%) and 20 weeks (14%) post-surgery in the high intensity group.
Ageberg & Roos (Ageberg and Roos, 2016)	15 females, 39 males. 36 post-ACL, 18 conservatively treated.	ACL reconstruction.	Cross sectional study. Correlation between knee confidence and physical measures.	Leg press, knee extension and knee flexion power.	Moderate negative correlation between greater knee extension power symmetry and confidence (r = -0.44) in the operated group only,
Hu et al (Hu *et al.*, 2017)	32 female, 58 male 18 to 37 year olds.	Low back pain.	Cross sectional study. Correlation between lumbar function and outcome measures.	Roland Morris disability questionnaire, visual analogue pain scale, isokinetic lumbar extension average power.	No significant correlation observed between average power in lumbar extension or flexion and pain and disability scores.

Thomee et al (Thomee *et al.*, 2012)	26 females, 56 males.	ACL reconstruction.	Cohort study. Tested at <3 months pre-surgery, and 6, 12 and 24 months post-surgery.	Leg press, knee extension and knee flexion power.	Significant differences in knee extension and flexion power up to 12 months (3.9 to 23.9%) restored by 24 months.
Chimenti et al (Chimenti *et al.*, 2016)	22 females, 18 males.	Achilles Tendinopathy.	Cross sectional study. 1 group of 20 with Achilles tendinopathy, 20 controls.	Stair ascent ankle plantar flexor power, and a VISA-A questionnaire.	Significantly lower peak ankle dorsiflexion power in Achilles tendinopathy group (29%). Moderate positive correlation between lower power and greater symptom severity (r = 0.53).
Di Stasi et al (Di Stasi *et al.*, 2013)	12 female, 30 male athletes.	ACL reconstruction.	Cross sectional study on those 6 months post-surgery comparing those who passed return to sport tests and those who did not.	3-D analysis of walking gait.	Significantly greater peak power during weight acceptance on uninjured limb compared to injured limb (values not reported).
Castanharo et al	29 males, 12 with ACL reconstruction >	ACL reconstruction.	Cross sectional study comparing previously	3-D analysis of bilateral CMJ and squat tasks.	Significantly lower peak knee power in ACL compared to non-injured

(Castanharo *et al.*, 2011)	2 years post-surgery, 17 uninjured.		injured and uninjured groups.		limbs (17%). Significantly greater hip-knee power ration in ACL compared to non-injured limb (12%).
Orishimo et al (Orishimo *et al.*, 2010)	13 males.	ACL reconstruction.	Cross sectional study, on reaching 85% of non-operated leg in hop for distance (4 to 12 months post-op).	Single-leg hop for distance sagittal plane hip, knee and ankle powers.	Significantly lower peak knee extensor power (48%), on takeoff on operated limb. Significantly greater peak knee flexion power (55%) during landing on operated limb.
Pratt & Sigward (Pratt and Sigward, 2017)	15 ACL reconstructed (7 female, 8 male), 15 uninjured (9 female, 6 male).	ACL reconstruction.	Cross sectional study. ACL group mean of 4.6 months post-surgery.	3-D analysis of self-selected speed 15m run and a single-leg land from horizontal jump cued to go as deep as possible in the landing.	Moderate positive effect for lower knee power absorption (ES = 0.49 using Cohen’s *d*) in non-operated side.

ACL - anterior cruciate ligament, CMJ - countermovement jump, ROM - range of motion, MSK - musculoskeletal, KOOS - knee injury and osteoarthritis score, VISA-A - Victoria institute of sport assessment - achilles, VISA - P - Victoria institute of sport assessment - patella

2.3.3 The role of power in cutting performance

When considering cutting performance, power has been given limited attention. Nine studies were found (summarised in Table 9) that measured power variables and investigated the relationship with cutting performance. Of those nine, only two studies measured power during the cutting task itself (Marshall *et al.*, 2014; Havens and Sigward, 2015a). Five other studies found significant relationships between greater power and enhanced cutting performance, but power in these studies was measured in jumping tasks (Hori *et al.*, 2008; Nimphius, McGuigan and Newton, 2010; Chaouachi *et al.*, 2012; Swinton *et al.*, 2014; Young, Miller and Talpey, 2015). The final two studies found no significant correlation between power and cutting performance (Young, James and Montgomery, 2002; Markovic, 2007).

When considering power within the cut itself, Havens & Sigward (Havens and Sigward, 2015a) found that greater hip frontal plane power significantly correlated with faster 90° cuts (r = -0.58) and higher hip sagittal plane power significantly correlated with faster 45° cuts (r = -0.48) among well trained soccer players. Marshall et al (Marshall *et al.*, 2014) found greater maximum ankle power within the cut significantly correlated with faster 110° cut times (r = 0.77). When considering power measured within other tasks, Young et al (Young, Miller and Talpey, 2015) found small correlations (r = -0.21) between greater relative power in the CMJ and faster 45° cut time alongside a moderate ability for CMJ relative power (ES = 0.61) to discriminate between faster and slower cut groups. Hori et al (Hori *et al.*, 2008) analysed relationships between 505-test times and relative and absolute peak power in the loaded (40kg) and unloaded countermovement jumps among 29 semiprofessional AFL players. A significant moderate (r = -0.38) correlation was seen between greater relative peak power in the loaded jump and faster 505-test times. No significant relationship between the power measures in the unloaded jump and 505-test performance were seen. Chaouachi et al (Chaouachi *et al.*, 2012) found a significant association with a small effect size (ES = 0.21) between greater peak power in the countermovement jump and faster performance in a 5m shuttle test. Tests were carried out on 23 elite soccer players and no significant relationship was observed between peak power and performance in the T-test. The authors also carried out a step wise regression that showed an 8-step model that included power (R^2 = 0.65) best explained performance in the T-test and a 10-step model also including power (R^2 = 0.72) best explained performance in the 5m shuttle test. This highlights the multifactorial nature of cutting performance. Swinton et al (Swinton *et al.*, 2014) performed correlational and regression analyses in a group of 30, well trained, but amateur rugby union players. They investigated the relationship between kinetic measures from speed deadlifts and squats to performance in the 505-test, jumps and sprints. Significant correlations were found between relative peak and average power in both the deadlift and squat and 505-test times, jump height and sprint times (r = -0.80 to -0.44). Average power in the deadlift showed no significant correlation with 505-test time and 10m sprint time. The regression analysis showed power measures to have no predictive ability in 505-test performance, however average power and peak power in the squat and the deadlift showed in the best two and three predictors of performance of 10m and 30m sprints. It was suggested that power showed greater relevance at the higher velocities seen during these sprints due to the shorter ground contact times when compared to the 505-test. The lack of relationship with 5m and 505-test times was explained by the need in these tasks to overcome inertia and that the ability to deliver force in a short period of time (power) was a more important quality at faster velocities. This explanation appears correct, particularly given maximum strength in both the deadlift and squat were the best two predictors of 5m and 505-test times. Finally, Nimphius et al (Nimphius, McGuigan and Newton, 2010) investigated the correlations between 505-test time and peak power in the jump squat at pre, mid and post season among ten female softball players. Jump squats were tested at bodyweight, with a bar and with 40, 60 and 80% 1RM added to the athlete. They found that peak power across the squats significantly correlated with 505-test times (r = -0.90 to -0.68) at mid-season with no correlation at pre-season and only with the non-dominant leg at post-season (r = -0.85 to -0.76). Peak power also showed significant relationships with 1RM squat at mid-season and post-season (r = 0.70 to 0.88) and with sprint times at mid and post-season (r = -0.97 to -0.76). It was suggested that at mid-season, athletes were in 'peak condition' and this accounted for the difference across time points and that peak power can only explain performance in cutting and sprints when this is the case. However, if peak power as measured in a jump squat were a consistent factor in 505-test performance, then the correlation should stay the same regardless of time of season. An alternative interpretation of these findings is that the correlation at mid-season was coincidental and that they are measures of separate abilities that peaked at the same time. While these studies show some correlations, the findings are not consistent, particularly when considered alongside the two studies that found no significant correlations between power measured in jumping with cutting performance in shuttle running, a lateral shuffle test and 45° cutting tasks (Young, James and Montgomery, 2002; Markovic, 2007). This mixed relationship is similar to that between power and jumping performance where different groups of variables have been shown to predict jumping performance depending on the jump (Johnston *et al.*, 2015). It is therefore possible that the task plays an important role in power production. This is supported by the finding that a closer relationship exists between power output and performance in jumping in trained compared to untrained individuals (Tessier *et al.*, 2013). It may therefore be necessary, in order to understand the relationship between power and performance, to measure it in the performance of the task itself rather than just test for correlations within another task. To date, only two studies have considered the relationship between measures of power and cutting performance doing so about individual joints. No studies have examined the relationship between the centre of mass power during the cutting task and cutting performance.

2.3.4 Conclusion

Deficits in power appear to be consistent in those rehabilitating from injury. This is similar to the differences in RFD discussed earlier in rehabilitating populations. Like RFD, power appears to also be a trainable quality in those rehabilitating from injury. To date, while a number of injuries have been investigated, no studies have analysed the role of power production in those rehabilitating from athletic groin pain. When considering cutting, the relationship between power and cutting performance is less clear. However, evidence points towards power production as being in part related to technical skill in a particular task rather than it being just a muscular quality. Only two studies have considered power within the cutting task itself in relation to cutting performance. Further work is needed to better understand this relationship.

Table 9: Studies investigating the role of power in cutting performance.

Author	**Participants**	**Study design**	**Performance tests**	**Results**
Chaouachi (Chaouachi *et al.*, 2012)	23 male elite soccer players.	Cross sectional study. Regression analysis of cut performance.	5m sprint, CMJ PP.	Large positive effect for CMJ PP between faster and slower 5m sprint groups (ES = 0.21 using eta squared). Regression analysis showed 8-step model including CMJ PP explained 65% of the variance in the T-test. A 10-step model including CM PP explained 72% of the variance in the 5m sprint shuttle.
Havens & Sigward (Havens and Sigward, 2015a)	12 female, 13 male soccer players.	Cross sectional study. Correlation between biomechanical measure and cut performance.	3D kinetic and kinematic analysis of 45° and 90° cuts sagittal and frontal plane	Moderate negative correlation between greater frontal plane hip power (r = -0.59), and faster 90° cut time. Moderate negative correlation between greater sagittal plane hip power (r = -0.48) and faster 45° cuts.
Marshall et al (Marshall *et al.*, 2014)	15 male hurlers.	Cross sectional study. Correlation between biomechanical measure and cut performance.	3D kinetic and kinematic analysis of the 110° change of direction.	Very large negative correlation between faster run cutting time and greater maximum ankle power (r = -0.77).

Hori (Hori *et al.*, 2008)	29 male semiprofessional AFL.	Cross sectional study. Correlation between hang clean, sprint, jump and cut performance.	CMJ PP, CMJ 40kg PP, 505-test.	Moderate negative correlation between 505 time and absolute and relative PP in the CMJ 40kg (r = -0.39 to -0.38) but not in relative PP or absolute PP the CMJ.
Markovic et al (Markovic, 2007)	76 physical education students.	Cross sectional study. Correlation between strength, explosive strength and cut performance.	Lateral shuffle, 20yd shuffle, SJ power, hopping power.	Small to moderate negative correlations between greater squat jump and hopping power and faster times in all cutting tasks (r = -0.35 to -0.15).
Nimphius et al (Nimphius, McGuigan and Newton, 2010)	10 female softball players.	Cohort study. Measurements taken and pre, mid and post-season for relationship between strength, explosive strength and cut performance.	Jump squat, jump squat with 40%, 60% + 80% of PP, 505-test time.	Large to nearly perfect negative correlations between greater peak power in jump squats significantly correlated with faster 505-test times (r = -0.90 to -0.68).

Swinton et al (Swinton *et al.*, 2014)	30 non-professional rugby union players.	Cross sectional study. Regression analysis of sprinting, jumping and cutting.	505-test, speed deadlifts and jump squats at variety of loads for average and peak power.	Moderate negative correlations between greater relative peak power in the deadlift and greater relative average and peak power in the jump squat and faster 505-test times (r = -0.48 to -0.4).
Young et al, 2002 (Young, James and Montgomery, 2002)	15 male field and court sport athletes.	Cross sectional study. Correlations between explosive strength and cut performance.	Bilateral and unilateral relative power in isokinetic squat, 8m sprint with 20°, 40°, 60° and 4 x 60° cuts.	No significant correlations between unilateral power and any of the sprint or cutting tasks. No significant correlations between bilateral power and all cutting tasks bar the 40° right cut.
Young et al, 2015 (Young, Miller and Talpey, 2015)	24 community level Australian rules footballers.	Cross sectional study. Correlations between physical qualities and cut performance.	45° reactive and pre-planned cuts, CMJ relative power.	Small negative correlations between greater relative power and faster cuts time (r = -0.21 to -0.12). Moderate effect for CMJ relative power (ES = 0.61 using Cohen's d) to discriminate between faster and slower cut groups.

CMJ - countermovement jump, SJ - squat jump, VJH - vertical jump height, AP - average power, PP - peak power, RSI - reactive strength index, RM - repetition maximum, PV - peak velocity, PF - peak force

2.4 Explosive strength - impulse

The final biomechanical measure of explosive strength to be reviewed is impulse. This section will give an overview of impulse and how it is calculated, it's role in rehabilitation and its relationship as a measure with cutting performance. It will highlight that there is limited literature using impulse as a measure in rehabilitation but that deficits are consistently observed in those recovering from injury and that there are directional specific aspects to impulse regarding athletic tasks.

2.4.1 Overview of impulse

Impulse is the measure of the change in momentum of a body and is derived using Newton's 2nd law. The equation for calculating this is:

$$Impulse = F.\Delta t = m.\Delta v$$

where F is the force applied to the object, Δt is the change in time over which the force is applied, m is the mass of the object and Δv is the change in velocity of the object. This can be calculated from a force-time graph by calculating the area underneath the curve for the assessed movement or portion of movement. As it is a calculated from a force-time curve, is can be assessed using both dynamic and isometric tasks.

A consideration when utilising impulse as a measure of explosive strength is that a greater value can be achieved by increasing the time over which force is applied or by increasing the amount of force applied over a given time. If impulse is increased by increasing the time taken to apply force, this could not be interpreted as an increase in explosive strength, where a short time period is implicit. However, if the time over which force is applied remains the same and impulse increases, this can only be achieved through a greater force production and so it is possible to reason that explosive strength is increased. It is therefore important to consider how changes in impulse are achieved. A benefit of utilising impulse over rate of force development is that is it not prone to the same issues with undulations in force production. Figure 5 shows a force-time trace from an isometric mid-thigh pull and highlights the issue with RFD measures being unable to account for the undulations or noise observed in the trace. Impulse calculates the area beneath the trace and therefore includes the undulations in the trace in the measurement.

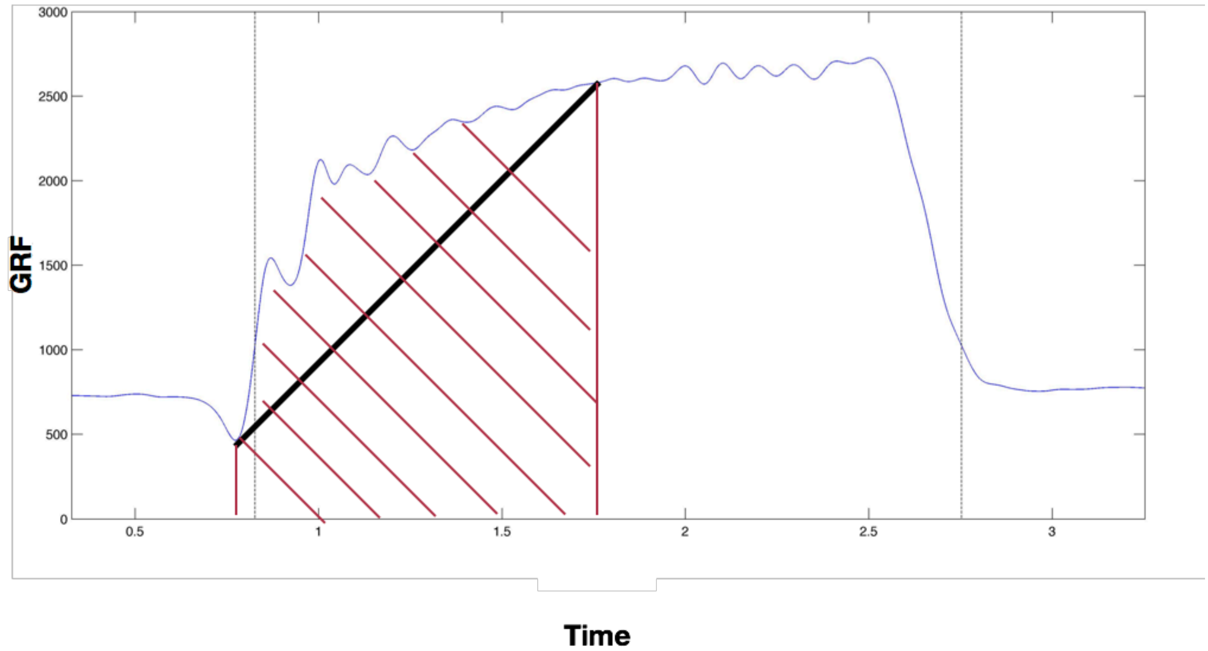


Figure 5: Force-time trace of an isometric mid-thigh pull (light blue line). Black line represents RFD measurement line, red lines indicate the area under the curve calculated for impulse

2.4.2 The role of impulse in rehabilitation

Impulse appears to be a variable that is not commonly measured within the literature around rehabilitation. As with power, it has most frequently been examined in populations rehabilitating from ACL reconstruction, likely due to the high levels of explosive strength required for return to play in field sports. However, only six studies could be found that measured impulse during explosive movements in ACL injured participants (Table 10). All six showed significant deficits in impulse (4 to 48%; ES = 1.3 to 1.82; χ^2 (41.0)) in the operated leg in jumping, running and cutting tasks compared to the non-injured leg (Dai *et al.*, 2014; Jordan, Aagaard and Herzog, 2014, 2016; Sigward, Lin and Pratt, 2016; Baumgart *et al.*, 2017; Baumgart, Hoppe and Freiwald, 2017).

Jordan et al (Jordan, Aagaard and Herzog, 2016) found significantly greater impulses in the non-operated limb during the late phase of squat jumping in previously ACL reconstructed elite ski racers. In another study on elite ski racers, it was found that previously ACL reconstructed athletes demonstrated significantly greater asymmetry in concentric impulse during the countermovement jump and in the later phase of the squat jump (4.3 to 8.8%) (Jordan, Aagaard and Herzog, 2014). Dai et al (Dai *et al.*, 2014) observed significant asymmetries in vertical and anterior/posterior impulses during both stop jump (17.7 to 22.8%) and cutting (8.8 to 11%) tasks in those 6-months post ACL surgery and Sigward et al (Sigward, Lin and Pratt, 2016) observed smaller knee extensor moment impulses during walking and running (ES = 1.3 to 1.82) in the operated limb approximately 4 months post-ACL reconstruction. Two studies from the same group found significantly lower impulses (4 to 16%) in the operated leg in vertical impulses across activities of daily living and jumping tasks (Baumgart *et al.*, 2017) and significantly lower concentric and eccentric (21 and 48%) impulses in the operated leg in those with lower scores on the IKDC questionnaire in bilateral jumping (Baumgart *et al.*, 2017).

When considering other injuries only three studies were found that investigated the role of impulse in injured populations (Suetta *et al.*, 2004; Stefanyshyn *et al.*, 2006; Opar *et al.*, 2013). In these studies, it was found that impulse is a trainable quality (27 to 32% increases observed) in those rehabilitating from hip replacement surgery (Suetta *et al.*, 2004), that significant deficits in knee flexion impulse (ES = 0.87 to 1.2) are present in those who have had prior hamstring injuries (Opar *et al.*, 2013) and that knee abduction moment impulses (24.5 to 49%) are greater in runners with patellofemoral pain, and in those who go on to develop patellofemoral pain (Stefanyshyn *et al.*, 2006). As with the other measures of explosive strength, deficits in impulse have been consistently observed between injured and non-injured limbs or participants. As with power, no studies have yet considered impulse in those with athletic groin pain. Also of note is that none of these studies considered the time component of impulse by considering time windows in the same way as discussed in measures of rate of force development.

Across all three biomechanical measures of explosive strength discussed in these sections (i.e. RFD, power, impulse), only six studies were found that tested the effect of interventions on measures of explosive strength in those rehabilitating from injury. All of these interventions were able to elicit increases in explosive strength. Given the apparent consistency in deficits observed in multiple musculoskeletal conditions, it is perhaps surprising that further investigations have not been undertaken. Future work should seek to understand the relationship between these measures of explosive strength and rehabilitation from injury.

Table 10: Studies investigating the role of impulse in rehabilitation.

Author	**Participants**	**Injury**	**Study design**	**Tests**	**Results**
Dai et al (Dai *et al.*, 2014)	14 females, 9 males.	ACL reconstruction.	Cross sectional study. Correlations tested at 6 months post-surgery.	3-D kinetic and kinematic assessment of a running stop jump and 35° cutting tasks.	Moderate to very large positive correlation between vertical and A/P impulse asymmetries (*r* = 0.57 to 0.85) and peak and average knee extension moment during the stop jump task. Significantly lower vertical and A/P impulses during both stop jump (17.7 to 22.8%) and cutting (8.8 to 11%) in ACL operated limb. Ability for vertical impulses during both tasks to predict knee moments (MAE = 11 to 19%).
Opar et al (Opar *et al.*, 2013)	26 male recreational athletes.	Prior hamstring injury.	Cross sectional study. Comparison between limbs 13 prior injured and 13 non-injured.	Early impulse during isokinetic knee flexion, EMG.	Moderate to large effects for lower impulses in injured limbs compared to non-injured (ES = 0.87, 1.2 using Cohen's *d*) at 50 and 100ms

					during 60deg.sec^{-1} knee flexion in injured limb.
Suetta et al (Suetta *et al.*, 2004)	15 elderly females, 15 elderly males.	Hip osteoarthritis.	12-week intervention. Three groups: (i) strength training, (ii) electrical stimulation, (iii) standard rehabilitation.	Isometric knee extension impulse.	Significant increase in impulse 30ms, 50ms, 100ms, 200ms in strength training group (27 to 32%). No significant increases seen in standard rehab and neuro-stimulations groups.
Jordan et al (Jordan, Aagaard and Herzog, 2014)	9 female, 9 male elite ski racers.	ACL reconstruction.	Cross sectional study. Nine previously injured approx. 2 years post-surgery, nine uninjured.	Countermovement jump and squat jump impulse measures and asymmetries.	Significantly greater asymmetry in concentric impulse CMJ and impulse during phase 2 of squat jump (4.3 to 8.8%) in previously injured athletes.
Sigward et al (Sigward, Lin and Pratt, 2016)	7 females, 5 males.	ACL reconstruction.	Cohort study. All participants were tested at 1 month, 3 months and at cleared for	3-D analysis of walking gait at first two time points and running gait at final testing.	Large negative effect for smaller knee extensor moment impulse during walking and running (ES = 1.3 to 1.82 using Cohen's *d*) in the operated limb.

			running (~4months).		
Jordan et al (Jordan, Aagaard and Herzog, 2016)	10 female, 12 male elite ski racers.	ACL reconstruction.	Cross sectional study. Eleven previously injured approx. 2 years post-surgery, eleven uninjured.	20 maximal consecutive squat jumps asymmetry index of impulse, EMG and height.	ACL reconstructed athletes demonstrated significantly greater later phase impulse on non-operated limb compared to early phase and landing phase (effect sizes not reported).
Baumgart et al (Baumgart *et al.*, 2017)	16 females, 34 males 1.5 to 3.5 years post-ACL surgery.	ACL reconstruction	Cross sectional study. Comparison between limbs and correlation with IKDC scores.	Kinetic analysis of sit to stand, step up and down and bilateral and unilateral CMJ.	Significantly lower impulse (4 to 16%) in the operated leg in sit to stand and jumping tasks. Moderate effect for lower IKDC group to show greater asymmetries in impulse (r = 0.33 to 0.46) in all tasks.
Baumgart et al (Baumgart, Hoppe and Freiwald, 2017)	12 females, 28 males 32 months post-ACL surgery.	ACL reconstruction.	Cross sectional study. Comparison of low and high IKDC groups.	Kinetic analysis of bilateral and unilateral CMJ, IKDC questionnaire.	Significantly lower operated leg eccentric and concentric (48 and 21%) impulses in low IKDC group.

Stefanyshyn et al (Stefanyshyn *et al.*, 2006)	40 runners.	Patellofemoral pain.	Cohort study. One group of 20 with PFP, one group of 20 asymptomatic. Prospective and retrospective. analysis	3-D analysis of running gait.	Significantly higher knee abduction impulses (24.5%) during stance phase in those with PFP. Significantly greater knee abduction impulses (49%) in those who developed PFP.

MAE - mean absolute error, A/P - anterior posterior, PFP - patellofemoral pain.

2.4.3 The role of impulse in cutting performance

Impulse has commonly been selected as a variable calculated from ground reaction force data measured during the cutting task itself. This is different to the types of analysis surrounding power and RFD and the relationships with cutting where the majority of literature has measured them in alternative movements and tested for correlations with cutting variables.

Five cutting studies were found that analysed impulse as a variable (Table 11). Three of these studies have investigated the relationship with cutting performance outcomes with two of these analyzing impulse in the cutting task itself (Havens and Sigward, 2015a; Spiteri *et al.*, 2015) and one analyzing impulse in the isometric mid-thigh pull (C Thomas *et al.*, 2015). One study investigated the differences between different cuts of different angles (Havens and Sigward, 2015c). Only one study was found that investigates the effects of an intervention on impulse and cutting performance (de Hoyo *et al.*, 2016).

Spiteri et al (Spiteri *et al.*, 2015) captured vertical ground reaction force data from a T-test, a 505-test and 45° reactive agility tests. They found that during 45° reactive agility tests, faster athletes showed lower vertical braking impulses (ES = 0.53) and greater vertical propulsive impulses (ES = 1.55). Within the T-test, faster athletes demonstrated greater vertical propulsive impulses (ES = 0.91). While this gives insight into the contribution of impulse towards enhanced performance outcomes, only vertical impulses were analysed. Havens & Sigward (Havens and Sigward, 2015a) considered impulse in all three planes in both a 45° and 90° cut. They found significant correlations between higher lateral impulse and shorter time to complete a 90° cut (r = -0.49). However, they only considered the decelerative phase of the cut which may mean that other aspects of force production during the propulsive phase that could be important for enhanced performance were missed. When considering impulse in alternative exercises, as done with power and RFD, only one study was found which investigated the relationship between impulses over 100 and 300ms during an isometric mid-thigh pull and performance in the T-test finding significant correlations between the two (r = -0.62 to -0.58) (C Thomas *et al.*, 2015). With such a small amount of literature surrounding impulse variables and their contribution to cutting performance, more work is needed to further understand the relationship between impulse in cutting and cutting performance. This is of relevance given observations in other athletic performance tasks. Greater impulses have been observed in the early part of stance phase of linear sprinting in elite sprinters compared to sub elite sprinters (Weyand *et al.*, 2010) and greater horizontal impulse ratios in faster linear accelerations (Morin *et al.*, 2015).

Of the remaining two studies, one investigated the difference between cuts of different angles. Havens & Sigward (Havens and Sigward, 2015c) analysed 45° and 90° cuts finding significantly larger lateral and anterior posterior impulses during both the approach and execution steps (51 to 140%) in the 90° compared to the 45° cuts. Understanding whether the differing demands of the cuts impacts the performance contributing factors may assist in informing training interventions, of which only one intervention study was found that considered impulse. De Hoyo et al (de Hoyo *et al.*, 2016) measured the effects of a 12-week eccentric training program on a group of soccer players compared to a control. All participants continued playing and training 4-5 times per week with the addition of 2 sessions a week of exercises for the experimental group. They found greater increases in total, braking and propulsive impulses in the experimental group (9 to 12%) compared to reductions in the control group (1 to 24%). Reductions in ground contact times (14 to 25%) were also observed suggesting that not only were impulses in the cut increased but, given ground contact times have been consistently correlated with performance (Marshall *et al.*, 2014; Dos'Santos *et al.*, 2016), that impulse and performance are linked. These last two studies highlight that cuts of different angle have differing force demands, that impulse during cutting can be influenced by training interventions.

2.4.4 Conclusion

Impulse appears to be the least researched explosive strength variable when considering both rehabilitation and performance. It would appear though that a similar pattern emerges in rehabilitation studies as with both RFD and power; namely, that deficits are present in populations rehabilitating from injury and that it is a trainable quality. The relationship between impulse and cutting performance has been given limited coverage and so no conclusions can be drawn. However, when considering the relationship between impulse and cutting performance, it should be measured in all three planes and in both the eccentric and concentric phases.

Table 11: Studies investigating the role of impulse in cutting.

Author	Participants	Study design	Performance tests	Results
Spiteri et al (Spiteri *et al.*, 2015)	12 female basketball athletes.	Cross sectional study. Comparison of faster and slower cutting groups.	505-test, T-test, 45° agility test vertical impulse variables.	Moderate effect of lower vertical braking impulse (ES = 0.53 using Cohen's *d*) and large effect of greater vertical propulsive impulse (ES = 1.55 using Cohen's *d*) for faster agility tests. Moderate effect for greater vertical propulsive impulses (ES = 0.91 using Cohen's *d*) for faster T-Tests.
Havens & Sigward (Havens and Sigward, 2015c)	12 female, 13 male soccer players.	Cross sectional. Comparison of 45° and 90° cuts.	3D kinetic and kinematic analysis of a run, 45° and 90° cuts.	Significantly larger lateral impulse during execution step and anterior posterior impulse during approach and transition steps (51 to 140%) in 90° compared to 45° cut.
Thomas et al (C Thomas *et al.*, 2015)	14 male collegiate athletes.	Cross sectional study. Correlation between IMTP and cut time.	IMTP impulse at 100 and 300ms, 505-test time.	Large negative correlations between greater IMTP impulses and shorter 505-test times (r = -0.62 to -0.58).

De Hoyo et al (de Hoyo *et al.*, 2016)	34 male soccer players.	Intervention study. Eccentric training and control groups.	60° and 45° cuts for total, braking and propulsive impulses, times and forces.	Increases in all impulses seen in the eccentric group (9 to 12%), reductions in impulses seen in control group (1 to 24%). Significant reduction in ground contact times in eccentric group (22%) but no control group.
Havens & Sigward (Havens and Sigward, 2015a)	12 female, 13 male soccer players.	Cross sectional study. Correlation between biomechanical measure and cut performance.	3-D kinetic and kinematic analysis of 45° and 90° cuts sagittal and frontal plane impulse.	Moderate correlation between greater frontal plane impulse reduced time in 90° cut (r = -0.49).

IMTP - isometric mid-thigh pull, RM - repetition maximum, ES - effect size

2.5 Methods of assessing explosive strength

Rate of force development (RFD), power and impulse are all variables it is that can be calculated from data gathered during a variety of tasks. All of these variables can be calculated from dynamic tasks. However, only RFD and impulse can be calculated from isometric tasks as power requires a displacement or velocity component in its calculation. The following section will review the isometric and dynamics methods available for gathering the data necessary to calculate these variables.

2.5.1 Isometric methods

Isometric methods are utilised as a method of measuring explosive strength as they allow consistency between subjects in technique as the joint angles at which force is produced are fixed. Rate of force/torque development is the predominant measure calculated from these methods in the literature although it is possible to calculate impulse. Isometric methods can be broadly categorised as whole-body and joint specific tests. Whole-body tests include the isometric mid-thigh pull (IMTP), the isometric squat and the isometric leg press. No studies could be found that measure explosive strength using the IMTP or isometric squat in rehabilitating populations. All of the literature, fifteen studies in all, utilised isometric unilateral joint specific methods of measuring explosive strength with respect to rehabilitation (Suetta *et al.*, 2004; Andersen *et al.*, 2009; Angelozzi *et al.*, 2012; Opar *et al.*, 2013; Winters, Christiansen and Stevens-Lapsley, 2014; Bie *et al.*, 2015; Jordan, Aagaard and Herzog, 2015; Kline *et al.*, 2015; Knezevic *et al.*, 2015; Blackburn *et al.*, 2016; Kadija *et al.*, 2016; Pua *et al.*, 2017; Rossi *et al.*, 2017; Cobian *et al.*, 2017; Friesenbichler *et al.*, 2017). Literature investigating the relationship between explosive strength and cutting performance utilising isometric methods is also limited. Only three studies utilising the isometric mid-thigh pull to capture explosive strength were found (Spiteri, Newton and Nimphius, 2015; Wang *et al.*, 2016; Townsend *et al.*, 2017). The IMTP been used commonly to assist in understanding athletic performance (McMaster *et al.*, 2014) and has shown good validity and reliability in a systematic review of 59 articles (Drake, Kennedy and Wallace, 2017). The relationship between whole-body explosive strength measured using the IMTP and rehabilitation from injury has yet to be explored. There is also a small amount of literature utilising the IMTP as a tool for measuring explosive strength in relation to cutting performance and no studies have considered the relationship across cuts of different angles

2.5.2 Dynamic methods

Dynamic methods offer the opportunity to assess explosive strength across broader ranges of motion and with the same two broad categories as isometric methods: whole-body movements such as jumping and isolated joint movements such as isokinetic dynamometry. Squat jumps, countermovement jumps and 1RM testing have been shown to be reliable whole movements used to measure explosive strength (Faigenbaum *et al.*, 2013). However, some variability in jump testing performance outcomes have been observed depending on the method of data capture used. Predicted jump height differences of 2-32% (ES = 0.08 to 2.27) have been observed across jump mats, force plates, video, accelerometers and jump and reach equipment (McMaster *et al.*, 2014). However, the use of 3D kinetic and kinematic data collection is considered the gold standard for measurement of for quantifying lower limb biomechanics (Munro, Herrington and Carolan, 2011) and has shown good to excellent reliability in dynamic tasks (Ford, Myer and Hewett, 2007).

Bilateral dynamic whole-body tasks are common and give an overview of the explosive strength qualities of the individual but, as with isometric measures, are unable to give an understanding of unilateral explosive strength. These are necessary as deficits in maximum strength and explosive strength, as discussed above, are common in the injured limb. When considering the measurement of explosive strength in rehabilitation, there is a large variety in the types of tasks selected with which to measure explosive strength. Eighteen studies were found that utilised dynamic methods. Six of these studies used bilateral methods, three used whole-body tasks to measure power (Castanharo *et al.*, 2011; Biernat *et al.*, 2013; Kristensen and Burgess, 2013), two used whole-body movements to measure impulse (Jordan, Aagaard and Herzog, 2014, 2016) and one used a joint specific movement to measure power (Hu *et al.*, 2017). Twelve studies utilised unilateral tasks to measure explosive strength with respect to rehabilitation. Six of these studies used unilateral joint specific methods to measure power (Pincivero, Heller and Hou, 2002; Barker *et al.*, 2012; Calder *et al.*, 2014; Ageberg and Roos, 2016; Blackburn *et al.*, 2016; Chimenti *et al.*, 2016; Bodkin *et al.*, 2017), three used unilateral whole-body methods to measure power (Di Stasi *et al.*, 2013; Bieler *et al.*, 2014; Pratt and Sigward, 2017), two used both whole-body and joint specific methods to measure power (Orishimo *et al.*, 2010; Thomee *et al.*, 2012) and three used unilateral whole-body methods of measuring impulse (Stefanyshyn *et al.*, 2006; Dai *et al.*, 2014; Sigward, Lin and Pratt, 2016). Despite the interest in explosive strength measures in relation to rehabilitation and injury, no studies have yet explored the relationship between dynamic measures of explosive strength in those rehabilitating from athletic groin pain.

When considering cutting performance, it is a unilateral task and so understanding the explosive strength qualities on the individual limb and relating them to the cutting leg would, from a face validity perspective, offer greater value in understanding the performance determining factors than a bilateral task. Fifteen studies were found exploring the relation with explosive strength utilised whole-body tasks. Eight studies utilised unilateral whole-body methods of measuring impulse in the cut itself (S. M. Sigward and Powers, 2006; Uzu, Shinya and Oda, 2009; Spiteri *et al.*, 2013, 2015; Spiteri, Hart and Nimphius, 2014; Havens and Sigward, 2015c, 2015a; de Hoyo *et al.*, 2016). No studies were found that used whole-body unilateral jumping to measure explosive strength in relation to cutting performance.

Further, from a face validity perspective during cutting, force production occurs with the foot positioned above the ground as part of the gait cycle prior to a forceful limb extension into the floor. Only three studies were found that utilised such a task in jumps with two using explosive strength measures (Johnston *et al.*, 2015) (Kariyama, Hobara and Zushi, 2016) and one using jump height (Delextrat and Cohen, 2009). None of these studies investigated the relationship between the jumping tasks and cutting performance. In fact, to this authors knowledge, no studies have yet investigated the relationship between unilateral whole-body measures of explosive strength and cutting performance. Understanding if limb specific relationships exist between cutting performance and explosive strength may affect the decision making of the practitioner seeking to develop cutting performance and explosive strength with their athletes.

2.5.3 Conclusion

Overall, a wide variety of tasks have been used to measure explosive strength in relation to rehabilitation and cutting performance. The selection of which tasks to use is split depending on whether rehabilitation or cutting performance is being considered. Isometric joint specific measures offer the ability to reduce movement variability, determine explosive strength assessment of small groups of muscles and is popular in rehabilitation literature. The use of more dynamic whole-body tasks is more popular when considering cutting performance. Given the aim of rehabilitation from injury is often to return to high levels of performance in sporting activities such as cutting, understanding the relationship that exists with performance in those returning from injury is necessary. The use of whole-body dynamic methods to measure and understand the role of explosive strength in rehabilitating populations returning to sport performance should be considered.

2.6 Reactive strength

The next section will review reactive strength and its relationship with rehabilitation and cutting performance. It will focus on the reactive strength index as a measure which is representative of how well an individual is able to effectively utilise the stretch shortening cycle (Flanagan, Comyns and Rugby, 2008). This quality is perhaps less relevant in some chronic musculoskeletal conditions such as low back pain as it is a quality more commonly associated with dynamic sporting activities (Flanagan, Ebben and Jensen, 2008). Given its association with dynamic sporting activities, it is therefore an important quality to explore in those rehabilitating from injury seeking a return to sport and in relation to sporting performance. This section will show that a small amount of literature exists investigating the relationship between rehabilitation and reactive strength as measured using the reactive strength index. The nature of the research to date means that no conclusions can be drawn on that relationship. In relation to cutting performance, while the evidence is quite mixed it points towards a relationship between higher levels of reactive strength and enhanced cutting performance.

2.6.1 Overview of reactive strength

The reactive strength index (RSI) is a measure of an individual's ability to quickly move between an eccentric and concentric movement (Young, 1995). It is commonly tested using a drop jump onto a force plate or jump mat and is calculated using the ground contact time and the jump height achieved:

$$RSI = \frac{jump\ height}{t_{contact}}$$

where $t_{contact}$ is the ground contact time. When performing the drop jump tests used to calculate RSI, participants are instructed to jump as high as possible while minimizing time on the ground (Pedley *et al.*, 2017). While this can limit the jump height achieved, it challenges the participants ability to move quickly from the eccentric to concentric phase of the movement. The RSI has demonstrated very high reliability (**α** >0.95) (Flanagan, Ebben and Jensen, 2008). The following sections will review the role of reactive strength in both rehabilitation and cutting performance.

2.6.2 The role of reactive strength in rehabilitation

There is a relatively small amount of literature that investigates the relationship between reactive strength and rehabilitation. While drop jump and hop tests are commonly used, ground reaction force variables such as peak force and performance outcomes such as distance are used more commonly than reactive strength measures (Ford *et al.*, 2007; Ortiz *et al.*, 2011; DiFabio *et al.*, 2017). Only four studies could be found that consider the relationship between reactive strength and injury (Flanagan, Galvin and Harrison, 2008; Raschner *et al.*, 2012; Setuain *et al.*, 2015; Lehnert *et al.*, 2017) (Table 12). Each of the four studies considered ACL injuries and with three of those studies finding no between limb differences in reactive strength variables.

Flanagan et al (Flanagan, Galvin and Harrison, 2008) observed the differences in reactive strength between a group of ten participants who had an ACL reconstruction approximately 27 months earlier and a group of non-ACL injured participants. They measured RSI in a drop jump movement using a force sledge apparatus set up with the participant lying supine angled at 30° to the ground. They found no significant difference (ES = 0.25) in any reactive strength measures between involved and uninvolved limbs or between groups at 27 months following ACL reconstruction surgery. This suggests that reactive strength, assuming some reduction in this quality immediately post-surgery, was fully restored by 27 months post-surgery. Although not directly measuring reactive strength, Setuain et al (Setuain *et al.*, 2015) did examine unilateral and bilateral drop jump ground contact times and heights corroborating the findings of Flanagan et al. They tested male and female elite handball players who were approximately six years post-ACL reconstruction surgery and compared them to a non-operated control group. No between limb differences were observed in either the male or female groups.

In a long term prospective study, Raschner et al (Raschner *et al.*, 2012) analysed performance testing data in 370 junior ski racers to understand risk factors for ACL injury in that group. Reactive strength was one of eight factors (core strength, leg strength, anaerobic performance, anthropometrics, flexion/extension ratio, jump power, leg strength asymmetry) found to explain 89.6% of the variance in ACL injury occurrence. The highly specialised nature of ski racing means that care should be taken when considering these results, the same variables may not be relevant in field sports where the sporting demands are very different. Lehnert et al (Lehnert *et al.*, 2017) used a fatiguing protocol to understand the effects on reactive strength. They found significant reductions in RSI measured from a 30cm box (ES = 0.4) following a fatiguing protocol in youth soccer players. It was suggested that this reduced reactive strength could lead to greater yielding during ground contact and greater anterior shear forces about the knee, which have been associated with ACL injury (Berns, Hull and Patterson, 1992), increasing risk of ACL injury.

The literature surrounding the reactive strength index and injury is sparse and, while suggesting that reduced reactive strength may be a risk factor in ACL injury, there is not enough evidence to state the case with certainty. The literature also does not extend outside of ACL injury and so there is no understanding of the relevance of reactive strength in other common injuries observed in sporting populations such as athletic groin pain. Given muscle pre-activation has been shown to regulate performance in tasks used to measure reactive strength (Hobara, Kanosue and Suzuki, 2007) and muscle pre-activation has been suggested to protect against injury (Hashemi *et al.*, 2010) there is justification to further understand the relationship between reactive strength and rehabilitation. It is therefore important to further understand the relationship that exists between reactive strength and rehabilitation to determine its relevance as a measure and its potential role in rehabilitation interventions.

Table 12: Studies investigating the relationships between reactive strength and injury.

Author	**Participants**	**Injury**	**Study Design**	**Tests**	**Results**
Flanagan et al (Flanagan, Galvin and Harrison, 2008)	4 females, 16 males.	ACL reconstruction	Cross sectional. 10 controls, 10 prior (~2 years) ACL reconstruction.	DJ and rebound jump, flight time, contact time, RSI. All were performed in a force sledge.	No significant difference between groups or between involved and uninvolved limb in any of the performance tests.
Raschner et al (Raschner *et al.*, 2012)	175 female, 195 male 14 to 19 year old skiers.	ACL injury.	Prospective study. Fitness battery performed 3 times yearly.	DJ RSI (from 40cm).	Factor analysis proposed eight factors predicting ACL injury (of which reactive strength was one) with 89.3% of explained variance in males and 89.9% of explained variance in females.
Lehnert et al (Lehnert *et al.*, 2017)	18 male youth soccer players.	Injury risk.	Intervention study. The effects of fatigue on strength qualities.	DJ RSI (from 30cm)	Moderate effect fatigue on reductions in RSI (ES = 0.4 using Cohen's *d*)

Setuain et al (Setuain *et al.*, 2015)	21 female, 22 male elite handball players.	ACL reconstruction.	Cross sectional. 12 ~6 years post-ACL surgery and non-ACL injured groups.	Bilateral and unilateral DJ height and ground contact time, triple hop for distance, unilateral crossover hop for distance.	Previously injured females demonstrated significantly shorter ground contact times (20%) in bilateral DJ. No significant differences were seen between male groups.

DJ - drop jump, ES - effect size, ACL - anterior cruciate ligament, EMG - electromyography, RSI - reactive strength index, CMJ - countermovement jump

2.6.3 The role of reactive strength in cutting performance

This section will highlight that, while the evidence is somewhat mixed, the literature points towards a relationship between greater reactive strength abilities and improved cutting performance. Eight studies were found that investigated the relationship between reactive strength measures and cutting performance (summarised in Table 13). Of these, only three studies observed significant correlations between greater reactive strength index (RSI) scores and enhanced cutting performance (r = -0.65 to -0.4) (Young, James and Montgomery, 2002; Delaney *et al.*, 2015; Young, Miller and Talpey, 2015). One regression analysis found RSI was among eight factors in explaining 99% of the variance in 505-test time and change of direction deficit (Emmonds *et al.*, 2017). Elsewhere, Maloney et al (Maloney *et al.*, 2016) observed no significant correlation between RSI and performance in a double 90° cutting task, however, in a regression analysis vertical stiffness, used as one measure of reactive strength, and height in a drop jump explained 63% of the variance in time to complete that task. Three other studies found no significant correlations between RSI cutting performance (Barnes *et al.*, 2007; Jones, Bampouras and Marrin, 2009; McCormick, 2014).

Of the studies that found significant and no correlations between reactive strength and cutting performance, no obvious differences between them were apparent in task selection with a range of cutting tasks used from 180° through to 20°. However, differences in the participant groups are present. The studies that found significant correlations tested professional rugby league players (Delaney *et al.*, 2015), field and court sport athletes (Young, James and Montgomery, 2002), AFL players (Young, Miller and Talpey, 2015). Those that found no significant correlations included two studies testing university students (Jones, Bampouras and Marrin, 2009; McCormick, 2014). It is possible that the importance of reactive strength in cutting performance increases as the technical proficiency in their sport increases, as reactive strength qualities develop and/or is dependent upon the demands of the task used. For example, if an athlete has 'poor' cutting technique through lack of practice, they may be unable to utilise the reactive strength qualities they may possess to the same extent as an athlete who is well trained in cutting tasks. Conversely, a poorly trained athlete that possesses low levels of reactive strength as measured in a drop jump, would likely not utilise reactive strength qualities during cutting as they do not possess capacity to do so. This should be considered in future work investigating the importance of this strength quality. Further evidence that lends weight to reactive strength being an important component of cutting performance are the results from regression analyses. Both Emmonds et al (Emmonds *et al.*, 2017) and Maloney et al (Maloney *et al.*, 2016) observed reactive strength to be factors that explained 99% and 63% of the variance in cutting performance respectively. These studies emphasise the multifactoral nature of cutting performance as explosive strength, maximum strength and anthropometric variables also made up the contributing factors explaining variance.

When considering changes in reactive strength qualities, a meta-analysis (Asadi *et al.*, 2016) found that plyometric interventions, which focus on developing reactive strength qualities, had a small to large effect on cutting performance with a mean large effect across 24 studies (ES = 0.26 to 2.8; mean ES = 0.96). This demonstrates that training reactive strength qualities has a positive effect on cutting performance. Of importance is the observation that biomechanical differences have been observed between cutting and drop jumps (Cowley *et al.*, 2006; Kristianslund and Krosshaug, 2013) highlighting the idea that it is likely that there are common contractile and neural properties tested in the drop jumps that have some transference to cutting performance rather than common technical abilities. The evidence for a relationship between cutting performance and reactive strength is mixed. This may in part be due to differences in athletic abilities of the tested populations to date. Future work should consider the sporting and training backgrounds of participants and recognise that technical ability in cutting and lack of training history may affect the relationship.

2.6.4 Conclusion

The literature investigating the role of reactive strength in rehabilitating populations is sparse and shows no clear relationship. Further work to increase our understanding of the relationship between this strength quality and injury is necessary. The relationship between reactive strength and cutting performance is mixed but some evidence is present that appears to point towards a relationship suggesting that any future work seeking to fully understand the performance of cutting tasks should include reactive strength as a measure.

Two studies found significant biomechanical differences between drop jumps and cutting tasks (Cowley *et al.*, 2006; Kristianslund and Krosshaug, 2013). One other study found increased RSI with a training intervention focused on deceleration with no change in performance observed (Lockie *et al.*, 2014). One meta-analysis was found that demonstrated a positive effect of plyometric interventions on cutting performance (Asadi *et al.*, 2016). Finally, one study found that muscle pre-activation during a hop cutting task was important for vertical force production (Serpell *et al.*, 2014).

Table 13: Studies investigating the role of reactive strength in cutting.

Author	**Participants**	**Study design**	**Performance tests**	**Results**
Delaney et al, 2015 (Delaney *et al.*, 2015)	31 male professional rugby league players.	Cross sectional study. Correlation between physical qualities and cut performance.	505-test, drop jump RSI.	Moderate negative correlation between RSI in the drop jump and 505-test time on both legs (r = -0.45 to -0.44).
McCormick et al, 2014 (McCormick, 2014)	23 male university students.	Cross sectional. Correlation between cut time and strength, reactive strength and explosive strength	Lateral shuttle test, DJ.	No significant relationship between drop jump and lateral shuttle test.
Maloney et al, 2016 (Maloney *et al.*, 2016)	18 males, recreationally active.	Cross sectional study. Correlation between stiffness measures and cut performance.	DJ vertical stiffness, RSI, height, ground contact time, double 90° cut time.	RSI not able to differentiate between faster and slower groups or showed any significant correlation with cutting performance.

Emmonds et al (Emmonds *et al.*, 2017)	10 elite female soccer players	Cross sectional study. Regression analysis of cut performance.	505-test time, change of direction deficit, DJ RSI and height.	Regression analyses were able to explain 99% of the variance of the 505-test (including drop jump height but not RSI) and change of direction deficit (including DJ height + RSI).
Young et al, 2002 (Young, James and Montgomery, 2002)	15 male field and/or court sport athletes.	Cross sectional study. Correlations between explosive strength and cut performance.	Unilateral and bilateral DJ RSI and 20°, 40° and, 60° cuts over 8m.	Mixed correlations were found between bilateral RSI and performance across the cuts (r = -0.4 to – 0.65). Higher correlations were seen between the right DJs and cuts off the right (r = -0.46 to -0.51) than on the left (r = -0.23 to -0.29).
Barnes et al (Barnes *et al.*, 2007)	29 female collegiate volleyball players.	Cross sectional study. Correlation between jump measures and cut performance.	505-test time, DJ reactive strength index, contact time, jump height.	No significant correlation between DJ variables and 505-test time.
Jones et al (Jones, Bampouras and Marrin, 2009)	38 university students, 5 females and 33 males	Cross sectional study. Correlation between maximum, explosive and	DJ height and RSI, 505-test.	No significant correlation between 505-test times and variables in the drop jump.

		reactive strength and cut performance.		
Young et al, 2015 (Young, Miller and Talpey, 2015)	24 community level Australian rules footballers.	Cross sectional study. Correlations between physical qualities and cut performance.	45° reactive and pre-planned cuts, 10m sprint, 3RM smith machine half squat, CMJ, DJ RSI.	Moderate negative correlation between RSI and pre-planned cut (r = -0.65 using Cohen's *d*). Large effect for reactive strength being able to discriminate between faster and slower cutting groups (ES = 1.63 using Cohen's *d*).

RSI - reactive strength index, CMJ - countermovement jump, RM - repetition maximum, DJ - drop jump, RMS - root mean square, EMG - electromyography, MVC - maximum voluntary contraction. Greyed out studies indicate no significant relationship between reactive strength and cutting performance

2.7 Deceleration

The ability to decelerate is an important component of cutting (Lockie *et al.*, 2014), it is required to decelerate the body of mass to arrest momentum in one plane, in order to allow acceleration in a new direction. This section will analyse the literature surrounding deceleration during running and landings in relation to rehabilitation and performance. There are many outcome measures that can measured during deceleration tasks including ground reaction force based measurements, joint specific kinetic and kinematic measures, time to stabilisation and the landing error scoring system (Laughlin *et al.*, 2011; Cortes *et al.*, 2012; Spiteri, Hart and Nimphius, 2014; Elias, Hammill and Mizner, 2015). This section though will focus on the kinetic and kinematic measures to maintain focus on the neuromuscular qualities during tasks. It will show that the majority of literature in rehabilitation has been focused on the knee and has predominantly focused on peak ground reaction forces, EMG and kinetic and kinematic measures about the knee. It will also highlight that shorter deceleration times appear to have a relationship with enhanced cutting performance.

2.7.1 Overview of deceleration

Within the literature, the methods of measuring deceleration appear to be split between measurements taken during landing tasks and those taken during cutting tasks. Of the eleven studies found that measure deceleration in relation to rehabilitation, all of them utilise a drop landing with ten studies using unilateral landings and one study using bilateral landings. Sixteen studies were found that considered deceleration in relation to cutting with all utilising measurements taken from the cutting task itself. There are a broad range of measures available when utilising biomechanical analysis of deceleration during landing and cutting tasks. The selection of which deceleration variables to measure in rehabilitation appears dependent upon the aims of the study. For example, Laughlin et al (Laughlin *et al.*, 2011) aimed to understand the effect of knee flexion angles during landing on ACL loading to potentially reduce ACL injury risk. They therefore collected EMG data to measure interaction between the recruitment of the quads and hamstrings, joint based biomechanical data to understand knee joint loading which is the site of the injury and ground reaction force variables to understand alterations in loading as a result of the different landings. In a similar way in cutting, measures are selected dependent upon the aims of testing for example Dos'Santos et al (Dos'Santos *et al.*, 2016) measured ground reaction force variables in the penultimate and cut steps aiming to understand the relationship of both with faster cuts. This section will show that deficits in deceleration ability are commonly observed in populations rehabilitating from lower limb injury. It will also show that deceleration appears important for ehnanced performance with shorter deceleration times appearing related to enhanced cutting performance

2.7.2 The role of deceleration in rehabilitation

The role of deceleration in rehabilitation has been investigated across post-knee surgery and ankle sprain populations and is summarised in Table 14. Of the eleven studies found eight investigated deceleration in relation to ACL injuries (Shin, Chaudhari and Andriacchi, 2007; Vairo *et al.*, 2008; Laughlin *et al.*, 2011; Webster *et al.*, 2012; Elias, Hammill and Mizner, 2015; Ithurburn *et al.*, 2015; Theisen *et al.*, 2016; Pozzi *et al.*, 2017). Two studies investigated deceleration in relation to ankle sprains (C Doherty *et al.*, 2014; C. Doherty *et al.*, 2014). One study investigated deceleration in relation to meniscectomy surgery (Ford *et al.*, 2014).

Pozzi et al (Pozzi *et al.*, 2017) found significantly lower power absorption at the knee (33%) and higher hip joint moment (8%) at 50% of landing and significantly lower knee moment (25%) and knee power (59%) in ACL group at 75% of landing. Ford et al (Ford *et al.*, 2014) found differences between limbs three-months post-meniscectomy with lower knee extensor moments (17%) and greater knee flexion angles (17%) utilised in the operated limb. Ithurburn et al (Ithurburn *et al.*, 2015) found that there were no significant differences between stronger and weaker groups in biomechanical measures in unilateral landings in those seven-months post-ACL surgery. Elsewhere, no differences were observed depending on strength, but significantly greater hip flexion and knee adduction moments at initial contact on limbs eighteen-months post-ACL reconstruction following fatigue (15% and 23%) (Webster *et al.*, 2012). Further supporting between limb differences post-ACL surgery, Vairo et al found significantly lower peak GRF (12 to 31%) and greater hip flexion (13 to 28%) in ACL-operated limbs twenty-one months post-surgery (Vairo *et al.*, 2008). The two studies observing those with ankle sprains found significant differences compared to controls at both the acute stage and six months post-injury. Acutely, significantly lower peak GRF in 0-200ms of landing in injured limb (10%) and increased hip flexion, knee external rotation and foot adduction in injured side (sizes not reported) compared to controls were observed (C. Doherty *et al.*, 2014). However, at six months post-injury, no differences in GRFs were observed but altered kinematics, significantly greater hip joint stiffness and lower hip joint moment (sizes not reported), were still present (C Doherty *et al.*, 2014). Two studies were found that looked at the effects of coaching softer landings. Elias et al (Elias, Hammill and Mizner, 2015) found that the softer landings resulted in significant reductions in vertical GRF, ankle plantar flexion moment, biceps femoris EMG and co-contraction index (ES = 0.32 to 1.13) and significant increases in hip flexion, knee flexion and ankle dorsiflexion in the soft landings (ES = 1.29 to 1.81). In similar findings, Laughlin et al (Laughlin *et al.*, 2011) found lower peak vertical and ACL forces (12 to 19%) and greater knee and hip flexion angles (26 to 34%) in the softer landings. While these findings show reductions in peak ground reaction forces, this is likely due to those forces being dissipated over a longer period of time. Reducing the rate of deceleration, while appearing to reduce knee loading, will result in a slower deceleration that may negatively impact performance (this will be discussed in the following section). When considering deceleration abilities with rehabilitating populations, particularly those returning to sporting activities, attention should be paid to its impact on performance. As is similar to the explosive strength qualities discussed above, it would appear that between limb differences can remain in both the kinetic and kinematic measures of deceleration from landings in those with ankle and knee injury. No studies have yet investigated deceleration abilities in populations with athletic groin pain. Although coaching cues on landings have shown changes in those kinematic and kinetic qualities during deceleration from landings, it is not yet known whether they can be changed over the long term in response to rehabilitation interventions.

Table 14: Studies investigating the role of deceleration in rehabilitation.

Author	**Participants**	**Injury**	**Study design**	**Tests**	**Results**
Elias et al 2015 (Elias, Hammill and Mizner, 2015)	20 female, 14 male recreational and competitive athletes.	ACL reconstruction.	Intervention study on the effects of cueing a soft landing.	Unilateral landing from 20cm box 3D biomechanical measures vastus lateralis and biceps femoris EMG %MVIC.	Moderate effect of softer landings lowering vertical GRF, ankle plantar flexion moment (ES = 0.65 to 1.13 using Cohen's *d*). Large effect of softer landings increasing in hip flexion, knee flexion and ankle dorsiflexion (ES = 1.29 to 1.81 using Cohen's *d*).
Theisen et al (Theisen *et al.*, 2016)	Six studies included on 102 ACL-injured and 86 controls.	ACL reconstruction.	Systematic review and meta-analysis of muscle activity onset.	Unilateral drop landings, decelerating from walking and running and unilateral hop for distance, EMG.	No significant differences in timing of muscle recruitment prior to decelerations.

Pozzi et al (Pozzi *et al.*, 2017)	34 females, 6 males.	ACL reconstruction.	Cross sectional study. 20 ACL reconstructed, 20 controls.	3D kinetic and kinematic assessment of unilateral drop landing from 30cm.	Significantly lower power absorption at the knee (33%) and higher hip joint moment (8%) at 50% of landing in ACL group. Significantly lower knee moment (25%) and knee power (59%) in ACL group at 75% of landing.
Doherty et al (C Doherty *et al.*, 2014)	26 females, 49 males.	Ankle sprain.	Cross sectional study. Comparison of 57 six months post-ankle sprain, 20 controls	Unilateral 40cm drop landing kinematic and kinetic analysis.	No significant difference in peak ground reaction force. Significantly greater hip joint stiffness and lower hip joint moment on injured side (sizes not reported).

Doherty et al (C. Doherty *et al.*, 2014)	15 females, 41 males.	Acute ankle sprain.	Cross sectional study. Comparison of 37 injured, 19 controls.	Unilateral 40cm drop landing kinematic and kinetic analysis.	Significantly lower peak GRF in 0-200ms of landing in injured limb (10%). Increased hip flexion, knee external rotation and foot adduction in injured side (sizes not reported).
Laughlin et al (Laughlin *et al.*, 2011)	15 recreationally active females.	ACL loading.	Cross sectional study. Comparison of coached stiff and soft landings.	EMG and 3D kinetic and kinematic analysis of unilateral 37cm drop landing.	Significantly lower peak ACL force (12%) and vGRF (19%), significantly greater hip and knee flexion angles (26 to 34%) in soft landings.
Shin et al (Shin, Chaudhari and Andriacchi, 2007)	Computer model.	ACL injury.	Computer simulation study.	Load on ACL during different directions of loading in a unilateral landing.	Posterior deceleration force can reduce ACL loading by reducing peak strain from quadriceps.

Ithurburn et al (Ithurburn *et al.*, 2015)	97 females, 43 males.	ACL reconstruction.	Cross sectional study. 103 seven months post-ACL surgery split into weak and strong quads groups, 47 controls.	3D kinetic and kinematic assessment of unilateral 31cm drop landing. Isometric leg extension peak force. KOOS questionnaire.	No significant difference in peak landing force or loading rate. Lower quads strength demonstrated worse pain and ADL scores.
Ford et al (Ford *et al.*, 2014)	4 females, 14 males.	Meniscectomy.	Cross sectional study. Comparison between 9 three months post-surgery, 9 controls.	3D kinetic and kinematic assessment of a bilateral 31cm drop landing. Isokinetic knee extension and flexion peak torque. IKDC questionnaire.	Significantly lower knee extensor moment (17%) in operated leg and greater knee flexion angle (17%) bilaterally in operated group. No significant differences in peak torque observed.
Webster et al (Webster *et al.*, 2012)	26 males.	ACL reconstruction.	Cross sectional study. Comparison of 15 males 18-months post-surgery, 11 controls.	3D kinetic and kinematic assessment of unilateral 30cm drop landing.	Significantly greater hip flexion and knee adduction moment on operated limb following fatigue at initial contact (15% and 23%). No

					other between group differences.
Vairo et al (Vairo *et al.*, 2008)	18 females, 10 males.	ACL reconstruction.	Retrospective study. 14 hamstring graft ACL reconstructions 21 months post-surgery, 14 controls.	3D kinetic and kinematic and EMG analysis of unilateral 30cm drop landings. Isokinetic hamstrings peak force.	Significantly lower peak GRF (12 to 31%) and greater hip flexion (13 to 28%) in operated limbs. No significant differences in muscle pre-activation or hamstring peak torque.

GRF - ground reaction force, vGRF - vertical ground reaction force EMG - electromyography, ES - effect size, MVIC - maximum voluntary isometric contraction, ACL - anterior cruciate ligament

2.7.3 The role of deceleration in cutting

The ability to decelerate is an important aspect of cutting for field and court sport athletes (Spiteri *et al.*, 2017). Deceleration abilities have been investigated in relation to cutting with the literature summarised in Table 15. Sixteen studies were found that investigated deceleration in relation to cutting. Three studies investigated the relationship with performance (Havens and Sigward, 2015a; Spiteri *et al.*, 2015; Dos'Santos *et al.*, 2016). Five studies investigated between group differences in deceleration with respect to cutting (S. Sigward and Powers, 2006; Ebben *et al.*, 2010; Green, Blake and Caulfield, 2011; Spiteri *et al.*, 2013; Spiteri, Hart and Nimphius, 2014). Three studies considered the differences in deceleration between cuts of different angles (Havens and Sigward, 2015c, 2015b; Jones, Herrington and Graham-Smith, 2016). Two studies observed changes in deceleration in response to training interventions (Lockie *et al.*, 2014; de Hoyo *et al.*, 2016). Two studies considered the relationships between landing and cutting (Jones *et al.*, 2014; Dai *et al.*, 2015). One final study considered the effects of altered cutting forces on deceleration loads (Qiao, Brown and Jindrich, 2014).

When considering the relationship between deceleration and performance, Havens et al (Havens and Sigward, 2015a) observed the performance determining factors of the early deceleration phase of the cut step during 45° and 90° tasks. They found greater hip sagittal power significantly correlated with faster 45° cut times (r = -0.48) and greater lateral impulse, hip rotation angle and hip frontal power significantly correlated with faster 90° cuts (r = -0.59 to -0.47). Spiteri et al (Spiteri *et al.*, 2015) considered ground reaction force variables and their relationship with performance during a series of cutting tasks. They found faster athletes in a 45° reactive agility test showed lower vertical braking impulse (ES = 0.53), although faster athletes in the same task also showed greater non-significant peak braking forces and shorter ground contact times suggesting the greater impulse observed was due to reduce time applying force. They also observed that faster athletes in the 505-test demonstrated significantly greater vertical braking and propulsive force (ES = 1.72 to 1.88). While the significant between group differences in force application varied between tasks, the one consistent finding across all tasks was that shorter ground contact times were observed in faster athletes in all tests (4 to 72%). Dos'Santos et al (Dos'Santos *et al.*, 2016) considered the performance factors of both the cut step and penultimate step of a 505-test. They found significantly greater penultimate step horizontal braking force (r = -0.34) and greater vertical braking force on the cut step (*r* = 0.45) significantly correlated with faster 505-test times. They also found shorter cut step ground contact times in the faster group compared to the slower group (ES = -2.54). While not conclusive, it appears as though ground contact time in deceleration is a relevant variable for cutting performance. Given the apparent importance of deceleration time in cutting performance, considering deceleration abilities at set time windows (in a similar way to RFD measures e.g. 0-25ms, 0-50ms etc) within the cut may add to the understanding of the decelerative phase of cutting. Particularly when considered alongside the literature around sprint performance where force production in the early portion of ground contact has been associated with enhanced performance (Clark and Weyand, 2014). Also worthy of further exploration, is to determine if a relationship between deceleration abilities measured during landings and cutting performance exists. If so, this would allow practitioners an alternative form of assessing the decelerative abilities of their athletes that is relevant to cutting performance.

A variety of between group analyses have been performed looking at deceleration abilities in cutting. Between gender differences have been found with significantly lower pre-contact hamstring to quadriceps timing ratio in a 45° cut in males (15%) (Ebben *et al.*, 2010). Spiteri et al (Spiteri, Hart and Nimphius, 2014) also observed differences in deceleration forces between males and females. Males demonstrated a significantly greater braking force and impulse in both cut steps of two consecutive cuts (ES = 1.80 to 2.53). Sigward et al (S. Sigward and Powers, 2006) investigated differences in the deceleration phase of a 45° cut step between experienced and novice soccer players. They found significantly smaller knee flexor, adductor and internal rotation moments (77 to 169%) and knee sagittal, frontal and transverse plane impulses (29 to 40%) in novice athletes. In a similar analysis considering skill level rather than experience, Green et al (Green, Blake and Caulfield, 2011) found that rugby union players who started for their team demonstrated significantly shorter brake leg ground contact time (12%) and that knee extension started earlier in ground contact in the brake leg (22%) compared to those that did not start for their team. These studies add to the discussion around the role of deceleration in cutting performance. Investigating between gender differences allows practitioners to better understand the differences in specific populations. With regards the latter studies it cannot be assumed that more experienced or starting athletes are better performers at cutting and so such studies cannot be viewed in the same way as those discussed earlier analyzing cutting performance.

Three studies have investigated the deceleration demands of the penultimate step compared to the cut step and in cuts of differing angles. Jones et al (Jones, Herrington and Graham-smith, 2016) looked at the differences in force production during the penultimate and cut step in 90° and 180° cuts. They found that greater average horizontal forces in the penultimate ground contact (r = 0.47 and 0.57) were significantly related to lower peak knee abduction moments in the cut ground contact for both turns. They suggest that there is a role in the step prior to the cut in preparing the body for an optimum position to make the final ground contact. Corroborating the above findings, Havens et al (Havens and Sigward, 2015c) demonstrated significantly greater braking impulses and posterior GRFs in the penultimate step compared to the cut step and in the 90° cut compared to the 45° cut (51 to 140%). Havens & Sigward (Havens and Sigward, 2015b) did not collect penultimate step data, however, they also found between cut differences. Significantly greater approach velocity and hip and knee flexion angles in a 45° cut compared to a 90° cut (36 to 102%) and significantly smaller ankle plantar flexion, hip abduction and trunk lean into 45° cut compared to the 90° cut (44 to 500%) were observed. These findings show that greater braking is required in cuts of greater angles and that the penultimate step, rather than the cut step, appears to be the one where greater proportions of the required deceleration is done.

Two intervention studies were found relating to deceleration in cutting. De Hoyo et al (de Hoyo *et al.*, 2016) found significant increases in relative peak braking and relative braking impulse (12 to 23%) and reduction in braking time (17%) during the cut step in soccer players that utilised eccentric training compared to a control group. The training group also reduced their ground contact times (14 to 20%) which was the main performance outcome measure. This demonstrates that the deceleration forces can be affected by training interventions. In the only other training intervention study, Lockie et al (Lockie *et al.*, 2014) investigated the effects of two agility training interventions on cutting, both using the same exercises but one where participants were coached to stop as fast as possible during each repetition. No between group differences were observed in 505-test times, however no biomechanical measures were taken so it is unknown whether braking forces were effected. Dai et al (Dai *et al.*, 2015) aimed to understand the effects of coaching 'softer' decelerations that involved greater knee flexion angles. It was found that a softer ground contact significantly increased knee flexion angles and reduced peak ground reaction forces (12 to 43%). However, it also significantly increased the stance time and decreased the approach speed during the cut and stop-jump, reduced the jump height during the stop jump and reduced the takeoff speed in the cut (5 to 33%). Given the findings above relating shorter ground contact times to enhanced performance it would appear that softer decelerations may well prove detrimental to performance. Given the low number of studies, more work is needed before conclusions can be drawn on the effectiveness of interventions on deceleration.

Of the remaining studies Qiao et al (Qiao, Brown and Jindrich, 2014) used an upper body harness to alter rotational inertia during cutting to understand the effects of deceleration. They found that increasing rotational forces in the direction of the cut had no significant reduction of braking forces. Jones et al (Jones *et al.*, 2014) compared the biomechanics in unilateral drop landings and in cutting with factors contributing to ACL injury in mind. They found significant correlation between peak knee abduction angles and moments in drop landing and cuts (r = 0.46 to 0.86).

2.7.4 Conclusion

A range of studies have been completed that highlight, as with maximum strength, explosive strength and reactive strength, that deficits in deceleration ability are commonly observed in populations rehabilitating from lower limb injury. Studies would also suggest deceleration being important for performance with shorter deceleration times appearing related to enhanced cutting performance. Given the importance of the time component, the measurement of decelerative forces over set time periods has yet to be investigated with only the whole ground contact of the penultimate step or the whole of the eccentric phase being measured. So far, only one study has demonstrated that changes in deceleration are possible following an intervention with further investigation needed to understand the relationship between training interventions and changes in deceleration abilities.

Table 15: Studies investigating the deceleration in cutting.

Authors	**Participants**	**Study design**	**Performance tests**	**Results**
Dai et al (Dai *et al.*, 2015)	18 female, 18 male recreational athletes.	Cross sectional. Comparison of a natural landings and soft landing with greater knee flexion during a jump and cutting task.	3D kinetic and kinematic analysis of a 45° cut and a stop jump task.	Natural landing resulted in the shortest stance times and greatest jump heights and take off speeds observed (5 to 31%) Significantly lower peak posterior GRF and knee extension moment, with significantly greater knee flexion angle at peak posterior GRF across all conditions (6 to 22%).
Lockie et al (Lockie *et al.*, 2014)	4 females, 16 males team sport athletes.	Intervention study. One group agility training, the other group agility training with enforced stopping.	CODAT time and T-test.	Small to large positive effect of training for both groups on cut and sprint tests (ES = 0.29 to 1.31 using Cohen's *d*). No significant difference between groups for sprint or cutting tasks.
Jones et al (Jones *et al.*, 2014)	20 female soccer players.	Cross sectional study. Correlation between drop landings and cuts	3D kinetic and kinematic analysis of 90° and 180° cuts and unilateral drop landing.	Moderate to very large correlation between peak knee abduction angles and moments in drop landing and cuts (r = 0.46 to 0.86).

Qiao et al (Qiao, Brown and Jindrich, 2014)	2 females, 5 males	Cross sectional study. Effect of altering rotation inertia on cut braking forces.	Rotational inertia and braking forces during 25° cut.	Increasing rotational inertia had no significant reduction of braking forces.
Green et al (Green, Blake and Caulfield, 2011)	23 male rugby union players.	Cross sectional study. Comparison of 13 starters and 10 non-starters.	3D kinetic and kinematic analysis of 45° cuts.	Significantly shorter brake leg contact time in starters (12%) and knee extension started earlier in ground contact in the brake leg in starters (22%).
De Hoyo et al (de Hoyo *et al.*, 2016)	34 male soccer players.	Intervention study. Eccentric training and control groups.	60° and 45° cuts for total, braking impulses, times and forces.	Increase in relative peak braking and relative braking impulse (12 to 23%) and reduction in braking time (17%) in eccentric group.
Ebben et al (Ebben *et al.*, 2010)	12 female, 12 male university students.	Cross sectional study. Comparison of EMG timing between males and females.	EMG analysis of quadriceps and hamstrings during a landing from a vertical jump and a 45° cut.	Significantly lower pre-contact hamstring to quadriceps timing ratio in the cut in males (15%). Significantly earlier quadriceps recruitment in males prior to landing (18 to 22%).

Sigward & Powers (S. Sigward and Powers, 2006)	30 female soccer players.	Cross sectional study comparing 15 with >8-years soccer and 15 with <5 years soccer.	3D kinetic, kinematic and EMG analysis of 45° cut.	Novices demonstrated smaller impulses at the knee in all three planes (29 to 40%) and smaller knee moments in all three planes (77 to 169%). They also demonstrated a greater co-contraction ratio (26%). No significant differences between groups for kinematic measures were observed.
Havens & Sigward (Havens and Sigward, 2015a)	12 female, 13 male soccer players.	Cross sectional study. Correlation between biomechanical measures and cut performance.	3D kinetic and kinematic analysis of braking phase of 45° and 90° cuts.	Moderate correlation between greater hip sagittal power and faster 45° cut times (r = -0.48). Moderate to large correlation between greater lateral impulse, hip rotation angle and hip frontal power and faster 90° cuts (r = -0.59 to -0.47).
Havens & Sigward (Havens and Sigward, 2015c)	12 female, 13 male soccer players.	Cross sectional study. Comparison between cuts of differing angles.	3D kinetic and kinematic analysis of run, 45° cut and 90° cut.	Significantly greater lateral impulse during execution step and anterior posterior impulse during approach and transition steps (51 to 140%) in 90° compared to 45° cut. Significantly larger sagittal plane GRFs (27 to 83%)

				and distances between centres of mass and pressure during the cut step (19%) in 90° compared to 45° cuts. Lower lateral centre of mass to centre of pressure distance in approach step (38%).
Havens & Sigward (Havens and Sigward, 2015b)	12 female, 13 male soccer players.	Cross sectional study. Comparison between cuts of differing angles.	3D kinetic and kinematic analysis of 45° and 90° cuts.	Significantly greater approach velocity, hip and knee flexion angles in 45° cut compared to 90° cut (36 to 102%), significantly smaller ankle plantar flexion, hip abduction and trunk lean into 45° cut compared to 90° (44 to 500%).
Jones et al (Jones, Herrington and Graham-Smith, 2016)	22 female soccer players	Cross sectional study. Comparison of penultimate and cut step.	3D kinetic and kinematic analysis of penultimate and cut 90° and 180° cuts.	Moderate to large correlation between greater average horizontal forces in the penultimate ground contact and lower peak knee abduction moments in the change of direction ground contact (*r* = -0.57 using standardised mean differences). Moderate to large effect for greater peak horizontal braking force, horizontal braking

				impulse, peak hip and knee flexion angles and peak plantar-flexor moments during penultimate step (ES = 0.61 to 1.91 using Cohen's *d*).
Dos'Santos et al (Dos'Santos *et al.*, 2016)	40 male sub-elite and college athletes.	Cross sectional study.	505-test time and GRF data.	Large correlation between greater horizontal peak force and cut step (*r* = -0.61 to -0.57) and faster cut times. Moderate to large effects for greater penultimate step HBF and cut step HPF in faster athletes (ES = 1.08 to 1.61 using Cohen's *d*). Moderate to large effect for lower cut step HBF and HBFR in faster athletes (ES = -1.5 to -0.61 using Cohen's *d*).
Spiteri et al (Spiteri, Hart and Nimphius, 2014)	12 female, 12 male semi-professional athletes.	Cross sectional study. Comparison of males and females.	Isometric back squat peak force, 3D kinetic and kinematic assessment of 1 step and 2 step reactive cuts.	Large to very large effect for males demonstrating greater braking force and impulse in 1 and 2 step cuts (ES = 1.80 to 2.53 using Cohen's *d*).

Spiteri et al (Spiteri *et al.*, 2015)	12 female basketball athletes.	Cross sectional. Comparison of faster and slower groups.	505-test, T-test, 45° agility test vertical impulse variables.	Small effect for faster athletes in the agility test showing lower vertical braking impulse (ES = 0.53 using Cohen's *d*). Large effect for faster athletes in the 505-test demonstrated showing greater vertical braking force (ES = 1.88 using Cohen's *d*).
Spiteri et al (Spiteri *et al.*, 2013)	12 female, 12 male recreational field sport athletes.	Cross sectional study. Split into stronger and weaker groups.	Isometric back squat peak force, 3D kinetic and kinematic assessment of 45° cut.	Moderate to large effect for greater vertical and horizontal braking impulse and horizontal braking force (ES = 0.99 to 1.31 using Cohen's *d*) in stronger athletes.

CODAT - change of direction acceleration test, HBF - horizontal braking force, HPF - horizontal propulsive force, HBFR - horizontal braking force ratio, ES - effect size, GRF - ground reaction force, EMG - electromyography

3 Cutting performance

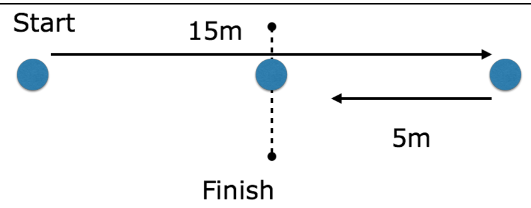
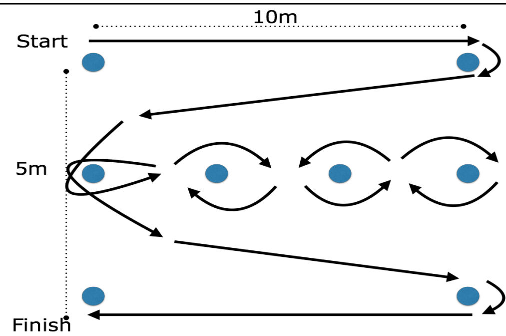
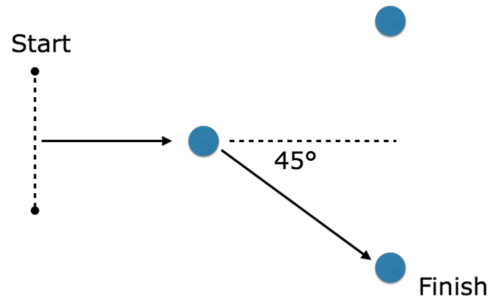
3.1 Overview of cutting

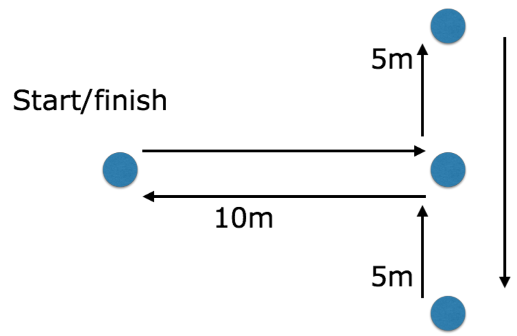
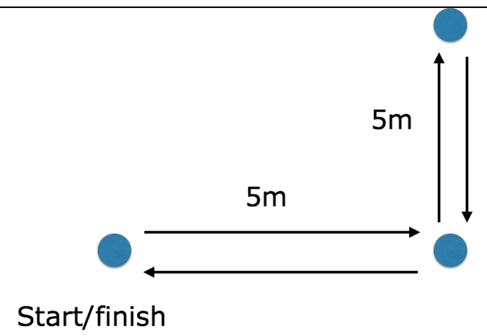
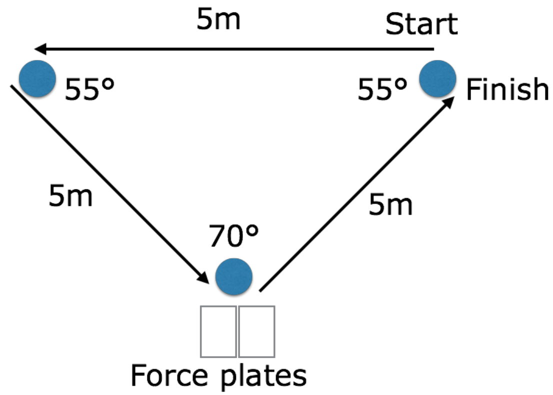
Cutting is a common task within field and court sports with cutting tasks shown to represent 20% of a basketball player's time on court (Mcinnes *et al.*, 1995) and over 700 cuts made by elite soccer players during a single match (Bloomfield, Polmam and O'Donoghue, 2007). Cutting tasks have been suggested to be a risk factor in a number of lower limb injuries including to the ankle, knee and groin (Gabbe *et al.*, 2004; Brown, Brughelli and Hume, 2014; Whittaker *et al.*, 2015). As such, work has been directed towards developing an understanding of the factors that may contribute towards the risk inherent in cutting. Further, the differences in those returning from injury have been explored in an effort to understand the aspects that may need to be considered during rehabilitation interventions. These areas will be explored in this section. Given the high frequency of the movements within competition, a body of work has also been conducted to understand the performance aspects of cutting in an effort to improve training interventions and therefore enhance performance. The biomechanical factors related to cutting performance will also be explored here.

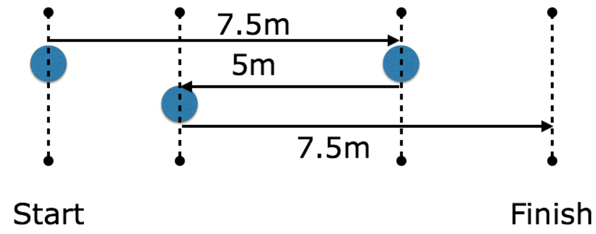
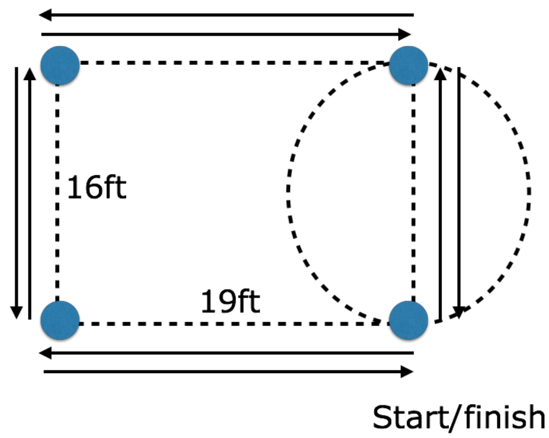
This section will consider the biomechanical factors within cutting that relate to both rehabilitation from injury and performance outcomes. The majority of literature when investigating these areas utilise 3D biomechanical analysis to obtain reliable measurements of cutting (Mok, Bahr and Krosshaug, 2017). Despite commonality in the measurement methods, a wide variety of tests have been used in order to measure cutting performance within the literature, these are shown in Table 16. Time to complete the test is the most commonly used measure of performance outcome. Alongside this, a wide variety of kinetic and kinematic variables used to describe the factors relating to both rehabilitation and performance.

The section will demonstrate that, in relation to injury, the majority of the literature considers injury risk by measuring cuts in non-injured populations e.g. factors that affect knee loading . A smaller body of research has analysed cutting biomechanics post-injury. The latter research will show that differences have been observed in cutting biomechanics in those post-injury and that it possible to change those biomechanics with training interventions. In relation to cutting performance, this section will highlight the wide range and large volume of variables related to performance making it relatively difficult to succinctly interpret results to impact the direction of training interventions.

Table 16: Explanation of cutting tests used within the literature

Test	Instructions	Schematic
505-agility test	15 metre straight line run prior to a 180° cut and a 5 metre acceleration back the way the athlete just came. Performance in the test is the time from 5m prior to the cut to 5m out of the cut	
Illinois agility test	The athlete starts face down on the ground, sprints forward and returns 10 metres each way, navigates an out and back cone slalom course before another out and back 10 metres each way.	
45° cut	Athletes move forwards in a straight line reaching a point at which they make a 45° cut. A variety of distances up to the cut have been used with times measured including total time, time from cut and, when reactive stimuli are used, reaction times and time from stimuli presentation to end point.	

T-Test	The athlete runs forwards 10 metres before moving into a side shuffle for 5 metres, then a side shuffle in the opposite direction for 10 metres, then another side shuffle back to the middle and backpedaling back to the start	
L run	The athlete sprints forwards 5 metres, makes a 90° cut, sprints another 5 metres before turning around a cone and completing the same course in the opposite direction.	
110° cut	The athlete sprints 5 metres along one side of a triangle, completes a 125° cut before a 5m sprint to the tested 110° cut with the foot plant occurring on a force plate and sprinting 5m out of the turn	

Modified 505-test	The athlete sprints forward 7.5m, completes a 180° cut, sprints 5m and completes another 180° cut before a 7.5m sprint to the finish	
Lane agility test	The starts by running forwards towards the end line, then side shuffles to the right, then backwards along the side of the key, then a side shuffle left to the point at which they started, then they complete the same course going back the other way around.	

3.2 The role of cutting in rehabilitation

Attempts have been made to understand the factors within cutting that relate to injury by use of retrospective video analysis (Krosshaug *et al.*, 2007; Waldén *et al.*, 2015) and by 3D biomechanical analysis (Clarke, Kenny and Harrison, 2015). However, given the role of both kinetic and kinematic biomechanical measures discussed in the above sections, the focus shall remain on literature that has made use of 3D kinetic and kinematic assessment. A total of thirty-five studies were found that investigated cutting biomechanics with respect to injury, these can be found in Table 17. The majority of these studies, twenty-eight in all, analysed cutting with respect to ACL injury. These comprised of five review articles (Brown, Brughelli and Hume, 2014; Hughes, 2014; Almonroeder, Garcia and Kurt, 2015; Pappas *et al.*, 2015; Sugimoto *et al.*, 2016), five intervention studies (Dempsey *et al.*, 2007, 2009; Cochrane *et al.*, 2010; DiStefano *et al.*, 2011; Souissi *et al.*, 2011) and fifteen cross sectional studies (McLean *et al.*, 1999; Besier *et al.*, 2001; Imwalle *et al.*, 2009; Donnelly *et al.*, 2012; Bencke *et al.*, 2013; Lee *et al.*, 2013; Stearns and Pollard, 2013; Tanikawa *et al.*, 2013; Weinhandl *et al.*, 2013; Frank *et al.*, 2013; Kristianslund and Krosshaug, 2013; Jones *et al.*, 2014; Kristianslund *et al.*, 2014; Clarke, Kenny and Harrison, 2015; Havens and Sigward, 2015a). Two of the twenty-eight studies that included the use of computer modelling techniques (McLean *et al.*, 2004; Weinhandl and O'Connor, 2017). Of the remaining studies, three investigated ankle instabilities (Dayakidis and Boudolos, 2006; Suda and Sacco, 2011; Koshino *et al.*, 2016) and four investigated athletic groin pain (Marshall *et al.*, 2016; Edwards, Brooke and Cook, 2017; King *et al.*, 2018).

Four of the reviews that were found consider the biomechanics of cutting with respect to knee loading. In one, the biomechanical risk factors between gender, surrounding the trunk and between planned and unplanned cuts were considered (Hughes, 2014). It was found that unplanned cuts can exaggerate the lateral trunk flexion and knee valgus movements thought to contribute towards injury, that greater trunk lateral flexion was associated with ACL injury and that females cut with greater knee extension and exhibit greater knee valgus and rotation angles and moments potentially placing them at greater risk than males. In agreement with these findings, two systematic reviews that considered knee loading during planned and unplanned cuts (Brown, Brughelli and Hume, 2014; Almonroeder, Garcia and Kurt, 2015) found greater knee flexion, abduction and internal rotation angles in unplanned conditions (ES = 0.04 to 0.95) with greater knee loading during unplanned cuts in all three planes (ES = 0.13 to 1.1). Sugimoto et al (Sugimoto *et al.*, 2016) reviewed biomechanical and neuromuscular characteristics with respect to ACL injury. They noted that cutting tasks involve knee flexion, valgus and internal rotation loads and that these movements are affected by actions at the hip. The final review investigated the effect of knee injury prevention programs on cutting biomechanics (Pappas *et al.*, 2015). Foot to centre of mass distance (6%), kinematic knee variables including adduction and rotation angles (14 to 80%), kinematic hip variables (11 to 14%), EMG glute recruitment (15 to 20%), kinetic variables (4 to 11%) were all found to change with injury prevention programs. These studies highlight the specific demands on the knee joint during cutting and that it is possible to alter a number of variables through interventions.

While a larger number of studies, mostly included in the reviews, have investigated cutting with respect to knee injury, the majority have considered this with uninjured populations. This was achieved by considering the aspects of cutting that affect knee loading. For example, greater horizontal forces during the penultimate step were found to significantly correlate (r = -0.57) with lower peak knee abduction moments during the cut step (Jones, Herrington and Graham-Smith, 2016). Dempsey et al (Dempsey *et al.*, 2007) found that peak knee valgus, internal rotation and flexion-extension moments were significantly greater (23 to 43%) in a wider foot placement and greater ipsilateral trunk flexion techniques. Differences between planned and unplanned cuts have been demonstrated with significantly greater hip abduction angle (57%) and knee valgus moment (51%), and lower internal rotation moment (33%) in unplanned cuts observed (Lee *et al.*, 2013). They investigated differences in knee loading between 45° and 90° cuts with significantly greater hip flexion ($F(1,37)$ = 52.34) and knee internal rotation ($F(1,37)$ = 87.0) in a 90° cut observed. Elsewhere, hip adduction moments have predicted 25% of the variance in knee abduction angles in both cuts highlighting the relationship between forces and movements at different joints (Imwalle *et al.*, 2009). Computer modelling techniques have been used to show that greater plantar flexion angles and greater anterior and medial positioning of the centre of mass relative to the foot reduces knee valgus loading (Donnelly *et al.*, 2012). In another modelling study, it was found that when posterior GRFs increased, significantly greater ACL force in all 3 planes and knee flexion were observed (change score = -1.6 to 0.54) (Weinhandl and O'Connor, 2017). Intervention studies have demonstrated the ability to alter cutting biomechanics with respect to knee loading in paediatric populations (DiStefano *et al.*, 2011) and in male field sport athletes (Dempsey *et al.*, 2007, 2009; Cochrane *et al.*, 2010) demonstrating that it is possible to alter the biomechanical aspects of cutting.

While these studies provide insight into ACL injury risk factors, only four studies were found that analysed previously ACL injured and non-injured participants. In similar observations as measures of explosive strength, two found differences between previously injured and non-injured groups. Significantly greater hip flexion (40 to 130%) and knee flexion angles and moments (22 to 25%) and lower knee rotation range (25%) and knee abduction moments (26%) were observed in a post-ACL reconstruction surgery group during cutting (Clarke, Kenny and Harrison, 2015). Elsewhere, significantly greater knee abduction angles (ES = 0.78) and peak knee adductor moments (ES = 1.31) in the post-surgery group were also observed (Stearns and Pollard, 2013). Lim et al (Lim, Shin and Lee, 2015) compared walking and running cuts between groups who had undergone ACL and posterior cruciate ligament (PCL) reconstruction surgeries at three and six months post-surgery. Significantly lower knee flexion angles, knee extension, valgus and external rotation moments, and ground reaction forces were observed in the PCL group compared to ACL and control groups at three months post-surgery. The final study investigating cutting in ACL injured populations, while not measuring 3D biomechanical data, analysed the impact of different training interventions on cutting performance outcome in those 4-6 months post-ACL surgery (Souissi *et al.*, 2011). It was found that a functional training group demonstrated significantly greater reductions in cut time (17% vs 13%) compared to a control training group. This study adds to the literature above that demonstrates cut biomechanics can be altered through interventions by highlighting that performance can also be positively affected.

When considering other injuries, three studies found significant differences in cutting biomechanics between normal and ankle instability groups. Significantly greater hip flexion, ankle inversion and medial gastrocnemius activity (ES = 0.94 to 1.73) was observed in an instability group compared to controls (Koshino *et al.*, 2016). Significantly greater vertical peak forces (ES = 0.79) and significantly shorter times to peak force (ES = -5) in unstable ankles during the 45° cut were observed (Dayakidis and Boudolos, 2006). While contradicting the previous study in that no significant difference in vertical peak force was observed, significantly lower peroneus longus recruitment (27 to 32%) was observed in the ankle instability group during a lateral cutting task (Suda and Sacco, 2011). These studies lend further weight to the idea that cutting biomechanics can be affected by injury and should be a consideration during rehabilitation of those seeking to return to activities where cutting is involved.

Another common injury associated with sports that involve cutting is groin pain (Whittaker *et al.*, 2015). Four studies were found that investigated cutting biomechanics in groin pain populations. Franklyn-Miller et al (Franklyn-Miller *et al.*, 2016) performed a biomechanical analysis of cuts from 322 participants with groin pain. They demonstrated that participants fell into three broad biomechanical clusters. One cluster demonstrated increased ankle inversion and external rotation, and knee internal rotation. The second cluster was characterised by greater hip flexion movements and the final cluster utilised reduced hip and knee flexion with greater contralateral hip drop. It was suggested that this could potentially mean that targeted interventions could be used to address the biomechanical aspects of each cluster. Adding to this work Edwards et al (Edwards, Brooke and Cook, 2017) investigated the differences between Australian rules footballers with and without a history of athletic groin pain. They used 3D analysis of unplanned 45° cuts to determine that those with groin pain displayed less knee flexion and hip internal rotation (ES = 0.61 to 0.94), and greater knee abduction, greater knee internal rotation, T12-L1 lateral flexion and rotation, vertical force and force in weight acceptance (ES = 0.67 to 1.17) when compared to those with no history of athletic groin pain. Another study demonstrated that hip and pelvis variables in the single-leg squat, often used as a screening tool, had no significant correlations with hip and pelvis variables within a 110° cutting task, a single-leg hurdle hop or a single-leg drop landing (Marshall *et al.*, 2016). The suggests that a single-leg squat is not able to provide insight into loading and movement about the hip and pelvis in cutting tasks. In another study (King *et al.*, 2018) found increases in contralateral side flexion and rotation, ankle dorsiflexion work and total ankle work (ES = -0.79 to -0.54) and reductions in hip flexion and ipsilateral side flexion (ES = 0.51 to 0.56) during a 110° cut following a rehabilitation intervention. Reductions in the Hip and Groin Outcome Score (HAGOS) (ES = 0.59 to 1.78) and increase groin squeeze (ES = 0.46 to 0.68) were also observed suggesting that it is possible to alter cutting biomechanics in groin pain populations and that these changes may play a role in rehabilitation from injury. The latter study implemented the same intervention that focused on strength, running and cutting technique to all participants. No studies have yet investigated the role of explosive strength development in those with athletic groin pain.

It can be surmised that the literature surrounding cutting biomechanics in relation rehabilitation follows a similar pattern to those observed within maximum strength, explosive strength, reactive strength and deceleration. Namely that alterations in cutting biomechanics are seen in those rehabilitating from a range of injuries and that it is possible to alter those biomechanics through the use of training interventions.

Table 17: Studies investigating the role of cutting in rehabilitation.

Author	**Participants**	**Study design**	**Tests**	**Results**
Souissi et al (Souissi *et al.*, 2011)	16 male athletes, 8 in functional training group, 8 in control group	ACL injury. Intervention study. Control group; strength, jumps, speed and proprioception. Functional training group; running, jumping, cutting and proprioception	T-test time, CMJ double and single-leg heights, squat jump height, five jump, triple hop and single hop for distance	Significantly quicker T-test (6%) in functional group with greater reduction (17% vs 13%) in time
Kristianslund et al (Kristianslund *et al.*, 2014)	125 female div 1 handball backs and wingers.	ACL injury. Cross sectional study. Correlations between biomechanical factors and knee loading.	3D kinematic and kinetic data of 6m acc 30° in towards a defender, receive a pass and sidestep 70° out past the defender.	Knee abduction moment increased with increased knee valgus (19%), hip abduction (6%), hip internal rotation (5%), torso lateral flexion (6%) and toe landing (17%). Alignment more important than force reduction for reducing knee abduction moments. Toe landing reduced moment arm of GRF.

DiStefano et al (DiStefano *et al.*, 2011)	28 females, 37 males.	ACL injury. Randomised controlled trial. Traditional same warm up each session strength, core, agility, balance and plyo Paediatric group had 3 phased progressions and used internal cuing.	3 trials of anticipated drop SL landing to 50-70° cut on dominant (kicking leg).	Moderate effect for paediatric group landed with lower knee external rotation (ES = 1.02 using Cohen's *d*) and greater knee internal rotation (ES = -0.86 using Cohen's *d*) during the stance phase. No other significant changes to technique.
Hughes (Hughes, 2014)	N/A	ACL injury. Review article. Biomechanical factors associated with ACL injury.	Studies reviewing ACL biomechanical risk factors.	Females cut with greater knee extension and exhibit greater knee valgus and rotation angles and moments. Greater trunk lateral flexion associated with ACL injury. Unplanned cuts can exaggerate the mechanics thought to contribute towards injury.
Brown et al (Brown, Brughelli and Hume, 2014)	6 studies.	Knee loading. Systematic review and meta-analysis.	Studies reviewed around knee mechanics in	Large effect on knee loading for knee flexor moments during IC (ES= 1.3 using Cohen's *d*), small effect

		Knee mechanics during cutting.	planned and unplanned cutting.	during weight acceptance (ES = 0.05 to 0.2 using Cohen's *d*). Trivial to moderate effects on knee loading of knee flexion, abduction and internal rotation angles (ES = 0.04 to 0.95 using Cohen's *d*). Small to moderate effects for knee abductor and internal rotator moments (ES = 0.13 to 0.88 using Cohen's *d*). Trivial to moderate effects for knee adductor moments (ES = 0.15 to 1.1 using Cohen's *d*).
Frank et al (Frank *et al.*, 2013)	15 females, 15 males who were physically active.	ACL injury. Cross sectional study. Relationship between hip and trunk biomechanics and ACL loading.	60° dominant leg cut from bilateral jump of 50% of height over a 17cm hurdle landing with one leg on the force plate.	Moderate to large correlations between higher knee varus moment and lower trunk rotation displacement (r = -0.46) and increased hip adduction moment (r = 0.83). Moderate to large correlation between greater knee external rotation moment and greater trunk flexion displacement (r

				= 0.42) and hip internal rotation moment (r = 0.59).
Besier et al (Besier *et al.*, 2001)	11 male amateur soccer players.	ACL injury. Cross sectional study. Comparison of planned and unplanned cut effects on knee loading.	3D kinetic and kinematic assessment of planned and unplanned 30° and 60° cuts.	Significantly greater knee flexion moments observed during unplanned 30° cut (6%) but lower during 60° cut (19%). Significantly greater knee internal rotation moments in unplanned cuts (49 to 129%). Valgus group experienced 55% greater valgus loads in unplanned.
Clarke et al (Clarke, Kenny and Harrison, 2015)	18 females, 18 males.	ACL reconstruction. Cross sectional study. Comparison of 18 who were 5 years post-surgery and 18 controls.	3D kinetic and kinematic analysis of a drop jump and unplanned 45° cut.	Significantly greater minimum and maximum hip flexion (40 to 130%) and maximum knee flexion angles (22%) and significantly lower knee rotation range (25%) in the post-surgery group during cutting. Significantly greater peak knee extension (25%) and lower peak knee abduction moments (26%) in the post-surgery group during cutting.

Lim et al (Lim, Shin and Lee, 2015)	30 participants.	ACL and PCL reconstruction. Cross sectional study. Comparison of 10 post-PCL reconstruction, 10 post-ACL reconstruction and 10 controls.	3D biomechanical analysis of running 180° cut and walking 45°, 90° and 135° cuts at 3-month and 6-month post-surgery.	Significantly lower knee flexion angle, knee extension, valgus and external rotation moments, and GRFs in PCL group at 3-months post-surgery (effect sizes not reported). No significant differences in knee extension, valgus and external rotation moments, GRF and knee flexion angles at 6-months post-surgery.
Stearns & Pollard (Stearns and Pollard, 2013)	24 female soccer players.	ACL injury. Cross sectional study. 12 who were 4 years post-surgery 12 controls	3D kinetic and kinematic analysis of a planned 45° cut.	Moderate to large effect of ACL operated athletes showing greater knee abduction angles (ES = 0.78 using Cohen's *d*) and peak knee adductor moments (ES = 1.31 using Cohen's *d*).
Cochrane et al (Cochrane *et al.*, 2010)	50 male Australian rules footballers.	ACL injury. Intervention study. One control, one balance, one machine based resistance and one	3D kinetic and kinematic analysis of planned 30° and 60° cuts.	Peak knee valgus and varus moments significantly reduced in training groups (8 to 62%). No significant differences between planned and unplanned conditions were observed.

		free-weights resistance.		
Tanikawa et al (Tanikawa *et al.*, 2013)	10 female, 10 recreational athletes.	ACL injury. Cross sectional study. Comparison between tasks and genders.	3D kinetic and kinematic assessment of hopping, cutting turning and sidestep and running (each with 90° turns).	Significantly greater knee anterior force and GRF in hopping than all other tasks (14 to 22%). Peak knee abduction and internal rotation angles were significantly greater in turning tasks compared to hopping (F = 4.79 to 9.16 using ANOVA). No significant differences between males and females.
Weinhandl et al (Weinhandl *et al.*, 2013)	20 recreationally active females.	ACL injury. Cross sectional study. Comparison of planned and unplanned cuts.	Isokinetic hip flexion, extension, abduction and adduction, knee flexion and extension and ankle dorsiflexion and plantarflexion peak torques. 3D kinetic and kinematic and EMG assessment of	Significantly greater total and sagittal peak ACL forces (11 to 19%) in unplanned cut. Significantly greater hip flexion and abduction in unplanned cut (6 to 54%). Significantly lower peak hip adduction moment (83%) in unplanned cut.

			planned and unplanned 45° cut.	
Bencke et al (Bencke *et al.*, 2013)	24 female handball players.	ACL injury. Cross sectional study. Comparison of dominant and non-dominant limbs.	3D kinetic and kinematic assessment of run and side cut task.	No significant asymmetries were observed between dominant and non-dominant legs.
Weinhandl and Connor (Weinhandl and O'Connor, 2017)	20 recreationally active females.	ACL injury. Cross sectional study. Computer models built using data used cuts to test the effect of altering GRFs.	3D kinetic and kinematic and EMG assessment of planned and unplanned broad jump with a vertical or lateral jump.	When posterior GRFs increased significantly greater ACL force in all 3 planes and knee flexion were observed (change score = -1.6 to 0.54). When vertical GRF increased significantly greater ACL force was observed (change score = 0.33). When medial GRFs increased, ACL total and sagittal plane force significantly decrease (change score = -1 to -0.31).
Kristianslund et al 2013(Kristianslund and Krosshaug, 2013)	120 female div 1 handball backs and wingers.	ACL injury. Cross sectional study. Comparison of drop jumps and cuts.	3D Kinematic and kinetic data of 6m acc 30° in towards a defender, receive a	Significantly greater (6 times) knee abduction moments in cut rather than DJ. Lower knee flexion angles, higher knee valgus and internal

			pass and sidestep 70° out past the defender and of drop jumps.	rotation angle at IC and maximums in cut. Moderate correlation between knee valgus angles in DJ and cut.
Donnelly et al (Donnelly *et al.*, 2012)	34 male football players.	ACL injury. Cross sectional study. Models tested using the nine participants with the greatest peak knee valgus moments during unplanned cut.	3D kinematic and kinetic data from planned and unplanned 45° cuts. Model created and changed to investigate effect on knee valgus moments	Knee valgus reduced by increased plantar flexion (7.9°), position centre of mass more medially to foot (3.1cm), ahead of the foot (1.4cm) and higher (0.2cm).

Pappas et al (Pappas *et al.*, 2015)	7 studies.	ACL injury. Systematic review and meta-analysis. The effect of injury prevention programs on cutting biomechanics.	Studies reviewed relating to ligament and quad dominance theories	Meta-analysis showed no effect of knee injury prevention programs on knee valgus and knee internal rotation. Foot to centre of mass distance found to change (6%), kinematic knee rotation variables (14 to 80%), kinematic hip variables (11 to 14%), EMG glute recruitment (15 to 20%), kinetic variables (4 to 11%) all found to change with injury prevention programs
Jones et al (Jones *et al.*, 2014)	20 female soccer players.	ACL injury. Cross sectional study. Relationship between cutting and landings knee valgus.	3D kinetic and kinematic analysis of 90° and 180° cuts and unilateral drop landing.	Moderate to large correlations between greater peak knee abduction angles in the cuts and landings and greater knee abduction moments in cuts and landings (r = 0.46 to 0.86).
Lee et al (Lee *et al.*, 2013)	30 male soccer players.	ACL injury. Cross sectional study. Comparison of 15 high level and 15	3D kinetic and kinematic assessment of	Significantly greater hip flexion angles (13%) in planned cut. Significantly greater hip abduction angle (57%), knee valgus moment

		low level players and between cut type.	planned and unplanned 45° cuts.	(51%) in the unplanned cut. Significantly lower internal rotation moment (33%) in unplanned cut.
Imwalle et al (Imwalle *et al.*, 2009)	19 female high school and college soccer players.	ACL injury. Cross sectional study. The relationship between hip and knee kinematics in cutting.	3D kinetic and kinematic assessment of 45° and 90° cuts.	Significantly greater hip flexion ($F(1,37) = 52.34$ using MANOVA) and knee internal rotation ($F(1,37) = 87.0$ using MANOVA) in 90° cut. Hip adduction moment predicted 25% knee abduction angles in both cuts.
Dempsey et al (Dempsey *et al.*, 2009)	12 male non-elite team sport athletes.	ACL injury. Intervention study. Six-week training to plant foot closer to centre of mass and maintain an upright torso.	3D kinematic and kinetic assessment of planned and un-planned 45° cuts.	Significant reduction in peak knee valgus moment (37 and 35%), foot to pelvis distance (6%) and torso lateral flexion (47 and 5%) in both planned and unplanned cuts.
McLean et al (McLean *et al.*, 1999)	14 female, 16 male state level athletes.	ACL injury. Cross sectional study. Comparison between genders.	Knee joint kinematic data from 30° to 60° cuts.	Females utilised significantly greater knee abduction during cuts (sizes not reported). Maximum knee flexion occurred 10% earlier in stance phase in females.

Dempsey et al (Dempsey *et al.*, 2007)	15 male amateur team sports athletes.	ACL injury. Intervention study. Comparison of cuts with enforced and normal techniques.	3D kinematic and kinetic assessment of planned 45° cuts with normal and enforced technique.	Significantly greater flexion extension moment with foot wide compared to foot close (23%), with normal step and toe out compared to toe in (24% and 48%). Significantly greater peak valgus moment with foot wide compared to normal (43%) and foot close (35%), with torso lateral flexion in opposite compared to same direction (27%), significantly greater peak internal rotation with foot wide (42%) compared to normal.
Havens & Sigward (Havens and Sigward, 2015a)	12 female, 13 male soccer players.	ACL injury. Cross sectional study. Correlation between cutting biomechanics and knee loading.	3D kinetic and kinematic assessments of 45° and 90° cuts.	Moderate correlation between greater lateral foot placement and greater knee adductor moments (r = 0.47) in the 45° cut. Moderate to large correlations between greater knee adductor moments and greater knee extension moments (r = 0.41) and hip rotations (r = 0.5) in the 90° cut. Moderate correlation between

				greater hip sagittal power and faster 45° cut times (*r* = -0.48). Moderate to large correlation between greater lateral impulse, hip rotation angle and hip frontal power and faster 90° cuts (*r* = -0.59 to -0.47).
Almonroeder et al (Almonroeder, Garcia and Kurt, 2015)	13 studies.	ACL injury risk. Systematic review.	A review of the effects of anticipation on knee loading during cutting.	Either increase or no difference in peak knee flexion in unplanned compared to planned cuts. Increased knee abduction observed in unplanned cuts. Either increase or no difference in knee internal rotation in unplanned compared to planned cuts.
Sugimoto et al (Sugimoto *et al.*, 2016)	N/A	ACL injury. Review article.	Broad review taking in cutting, jumping, game vs practice, playing surface, experience and prophylactics.	Flexion, valgus and internal rotation loads observed in cutting and these movements are affected by actions at the hip.

McLean et al (McLean *et al.*, 2004)	10 female, 10 male college basketballers.	ACL injury. Cross sectional study. Data used to model loading on ACL.	3D kinetic and kinematic assessment of 35° to 55° cuts.	Large effect for males showing larger knee internal rotation movement (ES = 1.87 using Cohen's *d*). Small effect for females showing larger knee valgus movement (ES = 0.58 using Cohen's *d*). Sagittal plane GRF perturbations did not increase anterior drawer forces to a level thought to injure ACL.
Koshino et al (Koshino *et al.*, 2016)	2 female, 18 male athletes.	Ankle instability. Cross sectional study. Comparison of 10 with ankle instability and 10 controls.	3D kinetic and kinematic and EMG assessment of 45° cut task.	Moderate to large effect for greater hip flexion and ankle inversion (ES = 0.94 to 1.25 using Cohen's *d*) observed in instability group. No significant differences in peak vertical GRF. Moderate to large effect for greater medial gastrocnemius activity (ES = 1.04 to 1.73 using Cohen's *d*) in instability group.
Suda & Sacco (Suda and Sacco, 2011)	2 female, 32 male	Ankle instability. Cross sectional study. Comparison	GRF and EMG assessment of lateral shuffle.	No significant difference in vertical force peak. Significantly lower

	professional basketballers.	of 16 with ankle instability and 18 controls.		peroneus longus recruitment (27 to 32%) in ankle instability group.
Dayakidis & Boudolos (Dayakidis and Boudolos, 2006)	32 male basketballers.	Ankle instability. Cross sectional study. Comparison of 15 with ankle instability and controls.	3D kinetic and kinematic assessment of 45° cut and side shuffles.	Significantly greater vertical force peak (18%) and shorter time to that peak (35%) in unstable ankles during the 45° cut. There were no between group differences in the shuffle.
Marshall2016 et al (Marshall *et al.*, 2016)	40 male field sports athletes.	Athletic groin pain. Cross sectional study. Relationship between SL squat variables and those across other tests.	3D kinetic and kinematic assessment of 110° cut, SL squat.	No significant correlations between hip and pelvis variables in the single-leg squat and any other test.
Edwards et al (Edwards, Brooke and Cook, 2017)	17 male AFL players.	Athletic groin pain. Cross sectional study. Comparison of groin pain and control.	3D kinetic and kinematic analysis of unplanned 45° cut.	Moderate effect for those with groin pain displaying less knee flexion and hip internal rotation (ES = 0.61 to 0.94 using Cohen's *d*). Moderate effect for those with groin pain to show greater knee abduction, greater knee internal rotation, T12-

				L1 lateral flexion and rotation, vertical force and force in weight acceptance (ES = 0.67 to 1.17 using Cohen's *d*).
Franklyn-Miller et al (Franklyn-Miller *et al.*, 2016)	322 male athletes.	Athletic groin pain. Prospective cohort study. Analysis of cutting biomechanics in those with groin pain.	3D kinetic and kinematic analysis of 110° planned cut.	Three broad clusters of movement pattern observed in those with athletic groin pain. Cluster 1 demonstrated increased ankle inversion and external rotation, and knee internal rotation. Cluster 2 utilising greater hip flexion movements. Cluster 3 utilised reduced hip and knee flexion with greater contralateral hip drop.
King et al (King *et al.*, 2018)	205 male field sports athletes.	Athletic groin pain. Intervention study. Effects of strength, linear running and cutting technique intervention.	3D kinetic and kinematic assessment of 110° cuts, groin squeeze, HAGOS.	Small to moderate effects for increases in contralateral side flexion and rotation and ankle dorsiflexion and total ankle work following the intervention (ES = -0.79 to -0.54 using Cohen's *d*). Small effects for reductions in hip flexion and ipsilateral side flexion

				(ES = 0.51 to 0.56 using Cohen's *d*), small to large effects for reduction in HAGOS score (ES = 0.59 to 1.78 using Cohen's *d*) and small to moderate effect for increased groin squeeze scores (ES = 0.46 to 0.68 using Cohen's *d*) following the intervention.

ES – effect size, HAGOS – hip and groin outcome score, SL – single-leg, EMG – electromyography, GRF – ground reaction force, ACL – anterior cruciate ligament, AFL – Australian rules football, DJ – drop jump, IC – initial contact, CMJ – countermovement jump, PCL – posterior cruciate ligament

3.3 Biomechanical factors relating to cutting performance

Attempts have been made to understand the biomechanical factors that relate to cutting performance. Developing this understanding could allow practitioners to design training interventions that seek to improve those key performance determining factors. A total of 15 studies were found that considered biomechanical variables from within the cuts themselves relative to cutting performance outcomes (Table 18). Of these, nine studies considered whole-body 3D kinetic and kinematic variables (Cowley *et al.*, 2006; Green, Blake and Caulfield, 2011; Sasaki *et al.*, 2011; Shimokochi *et al.*, 2013; Marshall *et al.*, 2014; Spiteri, Hart and Nimphius, 2014; Dai *et al.*, 2015; Havens and Sigward, 2015a; Condello *et al.*, 2016). Three studies considered ground reaction force variables (Spiteri *et al.*, 2013, 2015; Dos'Santos *et al.*, 2016). One study investigated the effects of an intervention (de Hoyo *et al.*, 2016). One study utilised 2D video analysis to investigate performance of a standing start 180° cut (Hewitt, Cronin and Hume, 2013). One final study investigated the EMG patterns during 90° cuts (Oliveira *et al.*, 2013).

From the studies that utilised 3D kinetic and kinematic variables a large number variables have been found that relate to faster cutting performance outcomes. Marshall et al (Marshall *et al.*, 2014) found that greater maximum ankle powers (r = 0.77), greater maximum ankle plantar moments (r = 0.65), smaller lateral pelvic tilt range of motion (r = -0.54), maximum thorax lateral rotation angle towards the change of direction (r = 0.51) and shorter ground contact times (r = -0.48) significantly correlated with faster 110° cut times. Havens & Sigward (Havens and Sigward, 2015a) found that greater frontal plane impulse (r = 0.49), greater hip rotation angle and frontal power (r = -0.59 to -0.47), and greater knee extensor moment (r = 0.50) correlated with faster 90° cut time. They also found that greater lateral foot placement, hip sagittal power and plantar-flexor and hip extensor moments (r = -0.48 to -0.39) correlated with faster 45° cuts. Sasaki et al (Sasaki *et al.*, 2011) observed significant correlations between less forward angular displacement between foot contact and maximum forward inclination (r = 0.61) and shorter ground contact times (r = 0.65) and faster 180° cuts. Shimokochi et al (Shimokochi *et al.*, 2013) defined performance during a lateral shuffle test as the ratio centre of mass velocity and ground contact time. They found significant correlation between enhanced performance and greater peak horizontal GRF (*r* = 0.73) and horizontal force angle (*r* = 0.59) and with lower vertical GRF at peak horizontal force (*r* = 0.54). Significant correlations were also observed between faster cuts and lower centre of mass positions (*r* = 0.48 to 0.59) and, in similar findings with those of Havens & Sigward (Havens and Sigward, 2015a), greater lateral distance between centre of mass and foot (*r* = 0.47). Elsewhere, Green et al (Green, Blake and Caulfield, 2011) compared starting to non-starting rugby players finding that starters demonstrated significantly shorter brake leg contact time (12%) and earlier knee extension during ground contact in the brake leg (22%). Cowley et al (Cowley *et al.*, 2006) compared soccer and basketball players finding soccer players demonstrated greater peak vertical GRF (F = 10.2) and lower ground contact time (F = 18.0) during 45° cuts. Condello et al (Condello *et al.*, 2016) found no significant difference in performance between males and females with ground contact time used as the performance measure during a 60° cut. They did find though that males demonstrated significantly greater medio-lateral ground reaction forces, cutting angles and minimum distance between the foot and centre of mass (ES = 0.76 to 1.05). Spiteri et al (Spiteri, Hart and Nimphius, 2014) also investigated gender differences but during a 45° cut finding a greater number of differences between groups. It was found that males produced significantly greater impulses, knee flexion, hip abduction and spine flexion (ES = 0.86 to 2.28). Males also demonstrated significantly faster time to peak propulsive force and between peak braking and propulsive forces (ES = 0.63 to 1.00), lower braking force (ES = 0.98) and greater propulsive force (ES = 1.13). Finally, Dai et al (Dai *et al.*, 2015) compared natural and a landing softly with greater knee flexion techniques during a 45°. Natural landings resulted in shorter stance times and faster take off speeds (12 to 39%) compared to landing softly with greater knee flexion. Significantly greater peak posterior ground reaction forces and lower knee flexion angles were observed in the natural cutting technique (20 to 27%).

Of the studies that considered ground reaction force variables, it was found that faster athletes are able to produce greater forces and demonstrate shorter ground contact times during cuts. Dos'Santos et al (Dos'Santos *et al.*, 2016) analysed penultimate and cut step kinetic data during the 505-test. They found that the horizontal braking force was the only variable during the penultimate step that significantly correlated (*r* = 0.34) with performance time. During the cut step, ground contact time (*r* = 0.70), vertical impact force (*r* = 0.45), horizontal propulsive force (*r* = -0.57) and braking force ratio (*r* = 0.43) correlated with performance time. They also split the participants into faster and slower groups with the faster group demonstrating shorter ground contact times and greater vertical impact force and horizontal propulsive forces (ES = 1.46 to 2.54). Spiteri et al (Spiteri *et al.*, 2015) took a similar approach splitting the participants into faster and slower groups comparing the two but only considered vertical ground reaction forces. They found faster athletes during the 505 COD test displayed significantly greater vertical braking and propulsive force compared with slower athletes (ES = 1.72 to 1.88). Faster athletes producing significantly lower braking impulse compared with faster athletes during the 45° cut (ES = 0.53) but significantly greater vertical propulsive impulse during both the T-test and agility test (ES = 0.91 to 1.55). Similar to the findings of (Dos'Santos *et al.*, 2016), the faster group also demonstrated significantly shorter ground contact times in all tests (8 to 19%). Finally, Spiteri et al (Spiteri *et al.*, 2013) split participants into stronger and weaker groups finding that the stronger group demonstrated significantly greater vertical and horizontal impulses, forces and angle of horizontal braking and propulsive forces (ES = 0.98 to 3.36) during a 45° cut. No significant differences were observed between groups in cutting time.

Of the remaining studies, Hewitt et al (Hewitt, Cronin and Hume, 2013) observed greater step frequency and no other biomechanical differences in faster athletes using 2D video analysis of a standing start 180° cut. De Hoyo et al (de Hoyo *et al.*, 2016) showed that 10 weeks of flywheel training led to significant increases in braking and propulsive forces, and impulses (9 to 12%), and reduced braking and propulsion times (14 to 25%). Finally, Oliveira et al (Oliveira *et al.*, 2013) used EMG alongside 3D biomechanical analysis to describe the muscle recruitment patterns throughout fast 90° cuts.

There are biomechanical variables that appear to be related to performance with some consistency. Shorter ground contact times in particular, and larger ground reaction forces alongside frontal plane kinetic and kinematic variables have been observed with some frequency. However, it is also apparent from the above literature that a very large number of variables have been measured and found to correlate with enhanced performance. This large number of variables makes it difficult for the practitioner implement interventions that aim to enhance performance as it is unknown if certain variables are more important than others for enhancing performance. Future work should consider analysis techniques that group variables in an effort to aid interpretation for practitioners.

3.4 Conclusion

This section highlights that the biomechanical factors within cutting are important to consider with respect to rehabilitation from injury but that a relatively low number of studies have considered this with rehabilitating athletes. They demonstrate, in general, that differences exist between those rehabilitating from injury and uninjured populations and that it is possible to alter cutting biomechanics through rehabilitation interventions. Of interest is the low number of studies considering the biomechanics of cutting relating to groin pain. When considering performance, a large number of variables have been suggested to be important for performance making it difficult for coaches to determine the most important factors to attempt to develop with their athletes.

Table 18: Studies investigating the relationship between cutting biomechanics and performance outcomes.

Author	**Participants**	**Study design**	**Performance tests**	**Results**
Havens & Sigward (Havens and Sigward, 2015a)	12 female, 13 male soccer players.	Cross sectional study. Correlation between biomechanical measure and cut performance.	3D kinetic and kinematic analysis of 45° and 90° cuts sagittal and frontal plane peak GRF, impulse and distance between centre of mass and centre of pressure	Moderate positive correlation between frontal plane impulse and faster time in 90° cut (*r* = 0.49). Moderate to large negative correlation between greater hip rotation angle and frontal power, and faster 90° cut time (*r* = -0.59 to -0.47). Large negative correlation between greater knee extensor moment and faster 90° cut time (*r* = -0.50). Moderate negative correlation between greater lateral foot placement, hip sagittal power, plantar-flexor moments and hip extensor moments, and faster 45° cuts (*r* = -0.48 to -0.39).
Marshall et al (Marshall *et al.*, 2014)	15 male hurlers.	Cross sectional study. Correlation between biomechanical measure and	3D kinetic and kinematic analysis of the 110° change of direction.	Moderate to very large correlation between faster cut time and greater maximum ankle power (*r* = -0.77), greater maximum ankle plantar flexion moment (*r* = -0.65), lower pelvis tilt range from initial contact to peak knee

		cut performance.		flexion (r = 0.54), greater maximum thorax lateral rotation (r = -0.51) and shorter total ground contact time (r = 0.48).
Sasaki et al (Sasaki *et al.*, 2011)	12 male collegiate soccer players.	Cross sectional study. Correlation between biomechanical measures and cut performance.	3D kinetic and kinematic analysis and time to complete 180° cut test.	Large positive correlation between lower forward angular displacement between foot contact and maximum forward inclination and faster cut time (r = 0.61). Large positive correlation between shorter ground contact time and faster cut time (r = 0.65).

Spiteri et al 2015 (Spiteri *et al.*, 2015)	12 professional female basketball players.	Cross sectional study. Comparison of faster and slower cutting groups.	505-test, T-test, 45° reactive cuts.	Large effect for faster athletes during the 505 COD test to display greater vertical braking force compared with slower athletes (ES = 1.88 using Cohen's *d*). Large effect for faster athletes during the 505 COD test to display greater vertical propulsive force (ES = 1.72 using Cohen's *d*). Small effect for faster to display lower braking impulse during the 45° cut (ES = 0.53 using Cohen's *d*). Moderate to large effect for faster athletes to display greater vertical propulsive impulse during both the T-test (ES = 0.91 using Cohen's *d*) and agility test (ES = 1.55 using Cohen's *d*). The faster group had significantly shorter ground contact times in all tests (8 to 19%).
De Hoyo et al (de Hoyo *et al.*, 2016)	34 male soccer players.	Intervention study. Eccentric training and control groups.	60° and 45° cuts for total, braking and propulsive impulses, times and forces.	Increases in all impulses seen in the eccentric group (9 to 12%), reductions in impulses seen in control group (1 to 24%). Similar patterns were seen in

				force and contact times with experimental group improving (14 to 25%) but the control group less so (0 to 7%).
Hewitt et al (Hewitt, Cronin and Hume, 2013)	22 u-21 court sport athletes	Standing start 180° change of direction acceleration	2D kinematic measures of a 180° change of direction acceleration	Smaller stride lengths (7%) and greater torso lean (30-37%) during acceleration. Higher stride frequency (4%) and greater knee drive (21-22%) in faster change of direction accelerations
Spiteri et al (Spiteri *et al.*, 2013)	12 female, 12 male recreational athletes.	Cross sectional. Split into a stronger and weaker group using isometric strength scores.	45° cut total, braking and propulsive impulse, peak braking and propulsive force, time to peak braking and propulsive force, angle of peak braking and horizontal propulsive force.	Moderate to large effect for stronger group to display greater vertical and horizontal impulses all apart from horizontal propulsive forces (ES = 0.98 to 1.77 using Cohen's *d*). Moderate to very large effect for stronger group to display greater peak vertical and horizontal peak forces, angle of horizontal braking force and propulsive force (ES = 1.1 to 3.36 using Cohen's *d*).
Spiteri et al (Spiteri, Hart and	12 female and 12 male semiprofessional	Cross sectional. Comparison of	Isometric back squat peak force, 3D analysis of reactive	Moderate to very large effect for males to display greater impulses (ES = 0.86 to 2.28 using Cohen's *d*). Moderate effect

Nimphius, 2014)	team-sport athletes.	males and females.	45° cut total, braking and propulsive impulse, peak braking and propulsive force, time to peak braking and propulsive force and between peak braking and propulsive forces.	for males to display faster time to peak propulsive force and between peak braking and propulsive forces (ES = 0.63 to 1.00 using Cohen's *d*), lower braking force (ES = 0.98 using Cohen's *d*) and greater propulsive force (ES = 1.13 using Cohen's *d*). Moderate to large effect for males to display greater knee flexion (ES = 0.97 using Cohen's *d*) and spine flexion (ES = 1.47 using Cohen's *d*) compared with females during all trials. Large effect for males to display greater hip abduction (ES = 1.14 using Cohen's *d*) during two-step offensive and defensive trials compared with females.
Oliveira et al (Oliveira *et al.*, 2013)	20 male recreational athletes.	Cross sectional study. Analysis of the motor modules involved during cutting.	3D kinetic and kinematic and EMG analysis of a 90° cut.	Module 1 prior to IC to decelerate knee joint flexion and stabilise trunk, module 2 at foot strike creating stability about the ankle knee and hip, module 3 related to impact, absorption and propulsion, module 4 related to push off via the

				lower posterior chain and module 5 throughout the whole cut related to ankle stability and maintaining an upright trunk.
Cowley et al (Cowley *et al.*, 2006)	30 female high school athletes.	Cross sectional study. Comparison of soccer and basketball players.	3D kinetic and kinematic analysis of drop jumps from a 31cm box and 45° cuts.	Soccer players demonstrated greater peak vertical GRF (15%) and lower contact time (28%) in the cuts. Knee valgus angle during the cuts was greater in both sports than the jumps (27.7%).
Dos Santos (Dos'Santos *et al.*, 2016)	21 sub elite rugby league players and 19 male collegiate athletes	Cross sectional study. Correlation between biomechanical measures and cut performance.	Kinetic measures during the penultimate foot contact and turning foot contact in 505-test, ground contact time and completion time	Large positive correlation between faster cut time and shorter ground contact time (r = 0.7), lower vertical impact force (r = 0.45) and greater horizontal propulsive force (r = -0.57) in the cut step. Moderate negative correlation between greater horizontal braking force in the penultimate step and faster cut time (r = -0.34). Moderate positive correlation between greater horizontal braking force ratio and faster cut times (r = 0.43).

Green et al (Green, Blake and Caulfield, 2011)	23 male rugby union players.	Cross sectional study. Comparison of 13 starters and 10 non-starters.	3D kinetic and kinematic analysis of 45° cuts.	Significantly shorter brake leg contact time in starters (12%) and knee extension started earlier in ground contact in the brake leg in starters (22%).
Dai et al (Dai *et al.*, 2015)	18 female, 18 male recreational athletes.	Cross sectional study. Comparison of a natural landings and soft landing with greater knee flexion during a jump and cutting task.	3D kinetic and kinematic analysis of a 45° cut and a stop jump task.	Natural landing resulted in the shortest stance times and greatest jump heights and take off speeds observed (5 to 39%) compared to softer landings. Significantly lower peak posterior GRF, greater knee flexion angle at peak posterior GRF and lower knee extension moment in soft landing trials (6 to 27%).
Condello et al (Condello *et al.*, 2016)	12 female, 14 male college soccer players.	Cross sectional study. Comparison of male and	3D kinetic and kinematic analysis of rounded and sharp 60° cuts.	No significant differences between males and females were observed for ground contact time. Moderate effect for males to display greater medio-lateral GRF, cutting angle and minimum distance

		female and between legs.		between the foot and centre of mass (ES = 0.76 to 1.05 using Cohen's *d*).
Shimokochi et al (Shimokochi *et al.*, 2013)	28 female college basketballers.	Cross sectional study. Relationship between performance and biomechanical measures.	3D kinetic and kinematic analysis of a lateral cutting task.	Performance defined as CoM velocity/GCT. Very large correlation between better performance and greater peak horizontal GRF (r = 0.73). Large correlation between better performance and greater horizontal force angle (r = 0.59) and with lower vertical GRF at peak horizontal force (r = 0.54). Moderate to large correlations between better performance and lower CoM (r = 0.48 to 0.59) and greater lateral distance between CoM and foot at toe-off (r = 0.47).

RFD - rate of force development, IMTP - isometric mid-thigh pull, EMG - electromyography, ES - effect size, RM - Repetition Maximum, GRF - ground reaction force, CoM - centre of mass, GCT - ground contact time, IC - initial contact

4 Athletic groin pain

Groin pain is a common clinical presentation that is seen among amateur and professional athletes (Waldén, Hägglund and Ekstrand, 2015). A systematic review revealed 33 different diagnoses in relation to groin pain and highlighted the need for clearer diagnostic criteria (Serner *et al.*, 2015). Attempts have therefore been made to provide clarity in defining the condition. In a consensus agreement, groin pain was organised into adductor related, inguinal related, iliopsoas related, pubic related, hip related and other cause categories (Weir, Brukner, *et al.*, 2015). This consensus statement attempts to give a clearer and narrower set of categories for groin pain in an effort to aid clinicians and researchers. The difficulty in doing this is the complex anatomy that exists around the groin with adductors, hip flexors and abdominals all crossing the pelvis. This is highlighted by the fact that many patients with groin pain present with pain in a number of anatomical areas (Falvey, King and Kinsella, 2015). Pain can be associated with passive structures such as the inguinal ligament or adductor longus tendon, alongside muscular injury such as adductor strains or articular changes such as labral tears (Almeida *et al.*, 2013; Weir, Holmich, *et al.*, 2015). In an effort to avoid reliance on a structural diagnosis, the term athletic groin pain (King *et al.*, 2015) has been used to describe all injuries in the inguinal region that are chronic in nature to a physically active population.

The condition has shown a high prevalence rate across multiple sports. It has an incidence of between 0.2 and 2.1/1000 hours in men and is the third most prevalent injury in soccer (Waldén, Hägglund and Ekstrand, 2015). High injury rates have also been seen in Gaelic Football (13.5/1000 hours) (Wilson *et al.*, 2007), in Rugby Union (2.5/1000 hours) (Brooks *et al.*, 2005) and Australian Rules Football (2.5/1000 hours) (Orchard and Seward, 2002). Given the high prevalence of the injury, further understanding the effects of rehabilitation interventions and the factors that cause the condition is important. This section will give an overview of the factors thought to increase risk for developing the condition as currently understood, and the intervention approaches used to rehabilitate it.

4.1 Athletic groin pain - contributing factors

A number of factors have been linked with athletic groin pain. A total of six systematic reviews were found that discuss the risk factors associated with athletic groin pain (Table 19) (Ryan, DeBurca and Mc Creesh, 2014; Diamond *et al.*, 2015; Orchard, 2015; Waldén, Hägglund and Ekstrand, 2015; Whittaker *et al.*, 2015; Kloskowska *et al.*, 2016).

Whittaker et al (Whittaker *et al.*, 2015) conducted a review consisting of a total of 29 studies finding that previous groin injury, reduced hip adductor relative to hip abductor strength and lower levels of sport training were the main risk factors. Ryan et al (Ryan, DeBurca and Mc Creesh, 2014) also noted weakness in adductor muscles and previous groin injury as prominent risk factors. They also found a number of hip range of motion and strength variables that were identified as risk factors further suggesting that strength could play a role in the development of the condition. Kloskowska et al (Kloskowska *et al.*, 2016) added further weight behind the idea that strength of hip musculature and range of motion about the hip are risk factors for the development of athletic groin pain within prospective and retrospective studies. They found that weak hip adductor muscles (ES = 1.00), decreased hip external rotation range of motions (ES = 0.43) and increased hip abduction range of motion (ES = 0.87) were observed in those who developed athletic groin pain. Two reviews covered the epidemiology of athletic groin pain. Walden et al (Waldén, Hägglund and Ekstrand, 2015) considered soccer athletes finding that the rate of injury was two-fold higher in males compared to females (RR = 2.4), a point echoed by Orchard et al (Orchard, 2015) who considered elite level team sports athletes (RR = 2.45). Finally, Diamond et al (Diamond *et al.*, 2015) investigated studies whose participants were diagnosed with femoral acetabular impingement (FAI). They found that those with FAI showed reduced hip range of motion towards flexion and internal/external rotation and reduced strength and endurance in hip flexion and adduction. Given the findings in the reviews discussed above, it is therefore possible that FAI could increase the risk of developing athletic groin pain. More recently, evidence has pointed towards other potential factors that may contribute towards athletic groin pain. Gore et al (Gore *et al.*, 2018) found that vertical whole-body, ankle, knee and hip abductor stiffness during a lateral hurdle hop task were all significantly lower (ES = 0.36 to 0.79) in those with athletic groin pain compared to a control group. The biomechanics of cutting with respect to groin pain has also been considered. Edwards et al (Edwards, Brooke and Cook, 2017) observed that those with groin pain displayed less knee flexion and hip internal rotation, greater knee abduction, greater knee internal rotation, T12-L1 lateral flexion and rotation, vertical force and force in weight acceptance (ES = 0.61 to 1.17) compared to those with no history of athletic groin pain. Greater asymmetries in hip adduction-abduction moments were also reported conference proceedings (Gore *et al.*, 2014) in those with athletic groin pain compared to a healthy control group. Outcome measures of explosive strength have been considered with no difference in countermovement jump heights observed in those with a history of groin injury compared to those without (Moreno-Perez *et al.*, 2017). However, no studies could be found that investigate the explosive strength measures discussed in previous chapters with respect to athletic groin pain.

Overall, the findings from the literature to date suggest that lower levels of strength and lower ranges of motion around the hip are consistently considered risk factors for the development of athletic groin pain. More recently, the literature has pointed towards evidence that lower levels of stiffness and alterations to cutting biomechanics are present in those with athletic groin pain. However, only one study has considered measures of explosive strength which, given the high velocity nature of movements involved in field sports in which athletic groin pain develops, warrants further investigation.

Table 19: Studies discussing risk factors related to the development of athletic groin pain.

Authors	**Participants**	**Study design**	**Results**
Whittaker et al (Whittaker *et al.*, 2015)	29 studies.	Systematic review. Overview of risk factors.	Previous groin injury, decreased hip adductor relative to hip abductor strength and reduced levels of sport specific training identified as main risk factors. Additionally, higher weight and BMI, reduced hip ROM and lower performance on fitness tests were also associated with greater risk.
Walden et al (Waldén, Hägglund and Ekstrand, 2015)	23 studies.	Systematic review. Epidemiology of groin injuries in soccer.	Rate of injury was 2-fold higher in males than females (RR = 2.4). Proportion of groin injury in males was 12.8% / 0.2 to 2.1/1000h, 6.9% / 0.1 to 0.6/1000h in females, meaning 2.4 higher rate of injury in males compared to females
Orchard (Orchard, 2015)	31 studies.	Systematic review. Comparison of genders in elite team sports.	Males had a higher incidence compared to females (RR = 2.45). Ice hockey appears to have the highest incidence of groin injury (17.1/1000h) compared to Gaelic football (5.8/1000h) and Australian rules (2.7/1000h).
Ryan et al (Ryan, DeBurca and Mc Creesh, 2014)	7 studies.	Systematic review. Risk factors in field sports.	Eleven risk factors identified. Three more prominent; previous hip/groin injury, older age, weak adductor muscles. Another eight; early maturing players, smaller dominant femur diameter, increased/decreased BM, decreased hip abduction and total rotation ROM, strength

			ratio of hip muscle groups, asymmetry in hip extension maximum strength, hip abduction and adduction with rotation maximum strength.
Diamond et al (Diamond *et al.*, 2015)	16 studies.	Systematic review. Activity limitations with FAI.	Reduced hip ROM towards flexion and internal/external rotation observed in those with FAI. Reduced strength and endurance in hip flexion and adduction has been observed in those with FAI. Post-surgical interventions may be required to utilise the greater range following surgery.
Kloskowska et al (Kloskowska *et al.*, 2016)	17 studies.	Systematic review and meta-analysis. Movement patterns and muscular function before and after groin pain.	Moderate effect for the association of athletic groin pain and weak hip adductor muscles (ES = 1.00 using Cohen's *d*). Small and moderate effect for decreased external rotation ROM (ES = 0.43 using Cohen's *d*) and increased abduction ROM (ES = 0.87 using Cohen's *d*) respectively to be associated with athletic groin pain.

ROM - range of motion, BM - bodymass, BMI - bodymass index, RR - risk ratio, FAI - femoral acetabular impingement, ES - effect size.

4.2 Groin pain rehabilitation interventions

Given the prevalence of groin pain described above, a large number of studies have been conducted investigating the effects of rehabilitation interventions. In an effort to pool this information, four review studies (Table 20), have been conducted (Almeida *et al.*, 2013; King *et al.*, 2015; Serner *et al.*, 2015; Charlton *et al.*, 2017).

In a comparison between surgical and non-surgical interventions, King et al (King *et al.*, 2015) found 56 studies in total, 27 of which were included in the meta-analysis. Depending on the injury and cohorts described, studies were subdivided into pubic, adductor and abdominal groups. Significantly faster (by 12.7 weeks) return to play times were observed for rehabilitation (ES = 1.3) compared to surgery in the pubic group, whereas there were no significant differences between surgery and rehabilitation in the adductor or abdominal groups. No significant difference in return to play rate between surgery and rehabilitation was observed in either the pubic, adductor or abdominal groups. Almeida et al (Almeida *et al.*, 2013) conducted a Cochrane review that comprised of two studies comparing the effects of exercise therapy and multi-modal/conventional physiotherapy. Both studies involved male athletes with longstanding adductor related groin pain with one finding significantly better results at 16-weeks follow-up for the exercise therapy group and the other finding no between group differences at 16-weeks. This disparity between the results of these two studies makes it difficult to draw conclusions as to the effectiveness of exercise treatments.

In a more recent review, Charlton et al (Charlton *et al.*, 2017) conducted a review of prevention and rehabilitation interventions. The 14 studies included in the review demonstrated a moderate strength of evidence towards exercise interventions for rehabilitation from athletic groin pain with those that included external loading of the hip and abdominal musculature appearing effective. Two of these studies were randomised controlled trials (RCTs). In the first, Holmich et al (Hölmich *et al.*, 1999) randomly assigned 68 athletes with athletic groin pain to active and non-active treatment groups. The active group performed local hip and abdominal strengthening exercises and the non-active group received laser treatment, manual therapy and stretching treatments. In the active group, 79% reported no groin pain post intervention compared to only 14% in the non-active group highlighting the greater effect of strengthening exercise over passive treatments. In the second, Weir et al (Weir *et al.*, 2011) also randomised 54 participants, into manual therapy and exercise therapy groups for 16 weeks of treatment. The exercise therapy group performed local hip and abdominal strengthening and a graded return to running program. The manual therapy group received manual therapy only. No significant differences between groups were observed however approximately 50% returned to sport in each group. These studies demonstrate that local hip and abdominal exercises can be effective in relieving symptoms, but the effect of interventions on performance when returning to play was not explored.

Seven case studies were included within the Charlton et al review (Charlton *et al.*, 2017) that utilised external loading of the hip and abdominal musculature. In a single-case study, McAleer et al (McAleer *et al.*, 2015) demonstrated successful return to play using local and whole-body strengthening exercises, alongside manual therapy and stretching alongside gradual return to running. Similarly, Rodriguez et al (Rodriguez *et al.*, 2001) published a case report with successful return to play using a combination of passive modalities and local hip strengthening alongside cardiovascular training. Vijaykumar et al (Vijayakumar, Nagarajan and Ramli, 2012) utilised 14-weeks of land and pool based exercises alongside local hip strengthening and whole-body strength training with a 15 year-old soccer player. Weir et al (Weir *et al.*, 2010) published a case series consisting of 44 athletes rehabilitating from athletic groin pain. They observed a 77% return to play rate with an average of 20-weeks with local hip and abdominal strengthening exercise and return to agility and linear running. Wollin et al (Wollin and Lovell, 2006) reported successful return to play in four 16 to 17 year-old football players over 13-weeks. In a similar approach they used local hip and abdominal strengthening prior to a return to running program. Woodward et al (Woodward, Parker and MacDonald, 2012) reported return to ice hockey following 7-weeks of local hip strengthening and return to skating. In a case series with three soccer players with sports hernias, Yuill et al (Yuill, Pajaczkowski and Howitt, 2012) observed return to play over 8-weeks of rehabilitation. Their rehabilitation consisted of a mix of passive treatments and local hip strengthening but was also the only study to include plyometric training. Overall, these treatments studies, both the RCTs and cases, demonstrate good outcomes with broadly similar approaches through the use of local hip and abdominal strengthening alongside gradual return to running. They all report success based on symptoms and return to play, but it is unknown whether performance was affected by these approaches. They also contain no whole-body strength or explosive strength aspects that are commonplace in interventions aimed at targeting performance improvements. Further work is needed to explore the impact of athletic groin pain on performance and understand how performance is affected throughout rehabilitation.

Given the risk factors associated with athletic groin pain discussed above, it follows that rehabilitation interventions that utilise external loading in an effort to strengthen musculature about the hip and abdominals, which have attachments and affect loading about the pelvis, should have some effect on this condition. Recently, explorations into the role of explosive strength have begun, however only related to acute injuries (Moreno-Perez *et al.*, 2017), and into cutting biomechanics (Franklyn-Miller *et al.*, 2016; Edwards, Brooke and Cook, 2017) in athletic groin pain. With regards to the latter, one study was found that investigated alterations in cutting biomechanics (King *et al.*, 2018) following a rehabilitation intervention in those with athletic groin pain. The intervention used local hip and abdominal, and whole-body strengthening exercises along with linear running and cutting technique training observing medium to strong effect sizes for greater trunk control and increased ankle work (ES = 0.51 to 0.79) as a result of the intervention. These changes were observed alongside concomitant improvements in symptoms (ES = 0.59 to 1.78) suggesting that a relationship may exist between alterations in cutting biomechanics and rehabilitation from athletic groin pain. However, this intervention contained no exercises specifically targeted at developing measures of explosive strength, nor did they examine explosive strength variables. The same is true of all of the intervention literature surrounding athletic groin pain and so it is unknown whether explosive strength is a quality that can contribute to rehabilitation from this condition.

Given the potential role for deficits in explosive strength observed commonly in rehabilitation and discussed in chapters 2.2 to 2.4, and in biomechanical factors discussed in chapter 3.2 within cutting, that have been associated with athletic groin pain, it is perhaps surprising that only one study to date could be found that sought to understand the effect of rehabilitation on cutting biomechanics. Further work is required to understand the effects of explosive strength training on the cutting biomechanics, outcome measures and performance of those rehabilitating from athletic groin pain.

4.3 Conclusion

The risk factors associated with athletic groin pain are varied. However, lower levels of strength and ranges of motion about the hip appear to be consistently related to the condition. The role of explosive strength measures and the effects on performance in those with athletic groin pain have received little attention to date and requires further exploration. With regards rehabilitation from athletic groin pain, exercise interventions appear to be effective particularly if they include strengthening exercises that utilise external loading. Again however, the use of explosive strength training in those with athletic groin pain and understanding how performance and whole-body neuromuscular strength qualities are affected throughout rehabilitation have yet to be explored.

Table 20: Review studies investigating athletic groin pain rehabilitation interventions.

Authors	**Study design**	**Studies**	**Results**
King et al (King *et al.*, 2015)	Systematic review and meta-analysis. Comparison of surgical and non-surgical interventions.	56 studies, 27 included for meta-analysis.	Similar return to play rate and faster return to play time in rehabilitation compared to surgery in pubic group. No difference in adductor and abdominal groups.
Charlton et al (Charlton *et al.*, 2017)	Systematic review. Exercise interventions for prevention and treatment of groin pain.	14 studies.	Moderate strength of evidence supporting the use of exercise intervention for rehabilitation from groin pain. Evidence of prevention is mixed although the application of external load to exercises appears advantageous. Poor reporting of intervention details.
Almeida et al (Almeida *et al.*, 2013)	Cochrane review. Conservative interventions for musculotendinous, ligamentous and osseous groin pain.	2 studies.	One study observed significantly better outcomes for exercise therapy compared to multi-modal treatment, the other did not.
Serner et al (Serner *et al.*, 2015)	Systematic review. Study quality in athletic groin pain.	72 studies.	Only 6% of studies were considered high quality. Significant correlation between lower quality study and higher treatment success. Moderate evidence for effectiveness of exercise in treating adductor related groin pain

5 Low back pain

Low back pain is one of the most common musculoskeletal conditions in the world with a prevalence rate of 18% reported (Hoy *et al.*, 2010). As such it has attracted a large amount of coverage within the literature. This section will give an overview of the physical and biomechanical factors that are thought to contribute to low back pain and the rehabilitation interventions that have been used treat it. It will show that multiple factors have been associated with low back pain and that the conditioning in the lumbar extensors is one of these factors. From a rehabilitation intervention perspective, it will show that a large variety of intervention types have been explored with strength training showing some positive outcomes. However, very few studies have explored the role of maximum strength training utilising free-weight resistance training.

5.1 Low back pain - contributing factors

A large number of factors have been associated with the development of low back pain and, given the prevalence, a large amount of work has been completed on the subject. Broadly, factors have been investigated relating to a variety of areas; patho-anatomical features within the spine itself, recruitment patterns of the musculature around the trunk, the conditioning of the muscles about the trunk, psychosocial factors and lifestyle factors. Systematic reviews have been completed around each of these areas and are shown in Table 21 (Hoogendoorn *et al.*, 2000; van Dieën, Selen and Cholewicki, 2003; Chen *et al.*, 2009; Fortin and Macedo, 2013; Steele, Bruce-Low and Smith, 2014a; Steffens *et al.*, 2014; Taylor *et al.*, 2014; Brinjikji *et al.*, 2015; Ract *et al.*, 2015; Ramond *et al.*, 2018)

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A major discussion point relating to low back pain has been the degree to which imaging is used as a diagnostic tool. Steffens et al (Steffens *et al.*, 2014) attempted to discover whether magnetic resonance imaging (MRI) findings are able to predict future low back pain. While they found no consistent association between degenerative changes at the spine and low back pain, they suggest that the current literature does not allow for definitive conclusions to be drawn regarding the importance of MRI findings due to a lack of large high-quality studies. One major issue surrounding spinal features observed in MRI is not related to those with low back pain but to the features observed in asymptomatic populations. Brinjikji et al (Brinjikji *et al.*, 2015) conducted a systematic review of imaging features of spinal degeneration in asymptomatic populations. They suggested that degenerative changes such as signal loss, disk height loss, disk protrusion and facet joint arthropathy are generally part of the aging process rather than pathologic processes that are a source of a person's low back pain. However, a high degree of disc degeneration and high intensity zones as observed on MRI were identified as risk factors for recurrence of low back pain (Hancock *et al.*, 2015). In another review relating to the value of MRI signs in low back pain, Ract et al (Ract *et al.*, 2015) also highlighted the high prevalence of spinal changes in asymptomatic participants and the low predictive value of patho-anatomical findings on MRI as being issues. They did find that in some specific circumstances, namely type one Modic and extensive edematous zygapophyseal changes, relevant correlations exist between MRI features and low back pain. These findings highlight the difficulty in relying on MRI features within the spine as a factor in low back pain and noted the potential for negative psychosocial impact from the pronouncement of medical findings (Ract *et al.*, 2015).

The impact on psychosocial factors is a necessary consideration as it is accepted that psychosocial factors play a role in low back pain (O'Sullivan, 2005). While not the focus of this review, it is necessary to recognise the role of psychosocial factors in low back pain as they are linked to the physical factors. Fear avoidance and negative beliefs have been shown as important factors influencing disability and pain in those with low back pain (Rainville *et al.*, 2011; Ng *et al.*, 2017). Psychosocial factors have also been shown to be associated with alterations to motor patterning with reduced lumbar flexion relaxation ratio observed in those with low back pain compared to controls (122% to 139%) (Watson *et al.*, 1997) and reduced lumbar flexion having been associated with higher levels of pain related fear (r = -0.55) (Geisser *et al.*, 2004) during a forward lumbar flexion task. Thomas & France (Thomas and France, 2007) found significant correlations between higher pain related fear and smaller lumbar excursions (sizes not reported) during standing reaching tasks. These data show a relationship present between motor patterns and fear of pain. Exercise interventions that target motor patterns should therefore consider addressing psychosocial factors that may interfere with their effectiveness.

Another physical area related to low back pain that is thought to be relevant are the biomechanics of different movements. Altered 3D biomechanical measures have been demonstrated in those with low back pain when compared to those without. Reduced range of motion (35% to 80%) and reduced velocity (43% to 48%) of thoracic flexion and increased range of motion (22%) and velocity (24%) of hip flexion was seen in seated downward and cross reaching tasks in those with low back compared with healthy controls (Crosbie *et al.*, 2013). In a standing cross reaching task (Song *et al.*, 2012) it was found that those without low back pain demonstrated greater pelvic rotation ranges (23%) than those with low back pain, they suggested that this difference may be a compensation to avoid further onset of pain. Significantly lower lumbar spine extension moments (25%) and higher axial rotation moments (115) along with lower lumbar and hip extension powers (Shum, Crosbie and Lee, 2007) and significantly reduced hip and lumbar velocities have been seen in completing sit to stand movements (38% to 53%) (Shum, Crosbie and Lee, 2005) in symptomatic participants. In another sit to stand analysis, Shum et al (Shum, Crosbie and Lee, 2009) showed an altered process for transferring power through passive and active mechanisms about the pelvis in those with low back pain. Symptomatic participants demonstrated lower capacity to transfer energy through the pelvis using passive power (21%). An interesting suggestion from the authors was that, in conjunction with the lower lumbar extension moments and powers, the reduction in load may lead to atrophic changes in the lumbar extensors. This latter point is discussed below. In all of the examples above, there are altered patterns of movement that seem to relate to a process of trying to alter loading and movement away from the source of pain, the lumbar spine. It is not known whether or not these differences are present prior to the onset of pain and the altered patterns and deconditioning eventually lead to increases of pain or whether they develop after the experience of pain begins. However, studies have yet to investigate the impact of exercise interventions on the 3D biomechanics of movement patterns in those with low back pain.

As mentioned above in relation to atrophic changes, the conditioning of the lumbar musculature has been investigated as a factor in relation to low back pain.

Conditioning in relation to low back pain has been described as strength, endurance and muscle physiology of the lumbar extensors with a reduction in these qualities known as deconditioning (Steele, Bruce-Low and Smith, 2014a). In relation to muscle physiology both fat infiltration and cross-sectional area have been investigated. Kjaer et al (Kjaer *et al.*, 2007) used MRI scans of the three lower lumbar levels from 850 participants and graded them for fat infiltration in lumbar multifidus muscles as none (0-10%), slight (10-50%) and severe (>50%). Associations (OR = 7.2 and OR = 3.6) were found between fat infiltration and those experiencing LBP ever or in the last year respectively. The lack of pain side related differences are difficult to explain if the assumption that fat infiltration is a cause of pain is taken. In order to explain either an ipsi-lateral or contra-lateral mechanism, fat infiltration on the pain side or opposite would be expected to be greater. This was not the case. Confounding things further is an apparent relationship with age. In an extension of the above Kjaer et al paper, Hebert et al (Hebert *et al.*, 2014) found an altered relationship between fat infiltration between a cohort at ages 40, 45 and 49 years old. At age 40, those with severe fat infiltration showed increased odds of experiencing back pain or leg pain, in the past year, at a non-trivial level. These associations were less consistent at ages 45 and 49. It was suggested that the results may have been confounded by the general increase in fat infiltration that is seen with age (Addison *et al.*, 2014). However, significantly greater levels of fat infiltration have been observed elsewhere in those with low back pain compared to healthy controls ($F(1,176) = 17.65$; 23.6% vs 14.5% fat) (Mengiardi *et al.*, 2006; Chan *et al.*, 2012). When considering the size of the musculature, there is some evidence that the lumbar paraspinal cross sectional area plays a role. Fortin & Macedo (Fortin and Macedo, 2013) conducted a systematic review of lumbar paraspinal cross sectional areas in symptomatic and asymptomatic patients. They found significantly smaller lumbar paraspinal (ES = -1.93) and multifidus (ES = -1.67) musculature in those with low back pain. Further supporting a potential role for lumbar deconditioning in low back pain is the consistent relationship between strength and endurance of the lumbar musculature and low back pain that was observed in the reviewed literature (Steele, Bruce-Low and Smith, 2014a). They found that seven of eight studies found significantly lower strength in those with low back pain compared to asymptomatic controls. These findings add strength to the idea that conditioning of the lumbar musculature is a factor in the development of low back pain and is in keeping with the findings discussed in the maximum strength section of this review. Namely, in rehabilitating populations it is common for reductions, or asymmetries, in strength to be observed. Low back pain rehabilitation interventions should therefore consider methods to address the conditioning of the lumbar musculature.

Table 21: Studies discussing risk factors related to the development of low back pain

Author	**Study design**	**Studies**	**Results**
Brinjikji et al (Brinjikji *et al.*, 2015)	Systematic review. Imaging features in asymptomatic populations.	33 studies.	Many findings of degenerative spine disease show high prevalence in asymptomatic population. All features increased with age.
Steffens et al (Steffens *et al.*, 2014)	Systematic review. Low back pain predictive ability of MRI features.	13 studies.	No consistent associations between MRI findings and the development of low back pain. No possible to draw firm conclusions due to methodologies.
Ract et al (Ract *et al.*, 2015)	Review. MRI signs in low back pain.	N/A	High prevalence of spinal changes in asymptomatic individuals. Low predictive value of MRI signs in development of low back pain.
Steele et al (Steele, Bruce-Low and Smith, 2014a)	Review. Reappraisal the deconditioning hypothesis.	39 studies.	Deconditioning of the lumbar extensors, in terms of strength, fatigue resistance and physiology, may be a common factor in low back.
Ramond et al (Ramond *et al.*, 2018)	Systematic review. Psychosocial risk factors in primary care.	23 studies.	Depression and psychological distress can impact the evolution of low back pain, passive coping strategies and fear-avoidance beliefs were predictive of persistent disability.
Van Dieën et al (van Dieën, Selen	Analysis of literature. Trunk muscle activation in low back pain.	30 studies.	Muscle activation was not predicted by the pain adaptation model or with the pain-spasm-pain model. Wide variance in trunk muscle across participants.

and Cholewicki, 2003)			
Hoogendoorn et al (Hoogendoorn *et al.*, 2000)	Systematic review. Psychosocial factors at work and in private life.	13 studies.	Low social support in the workplace and low job satisfaction evident as risk factors.
Taylor et al (Taylor *et al.*, 2014)	Systematic review and meta-analysis. Risk factors for first time incident of low back pain.	41 studies.	Multiple risk factors, many non-modifiable, with low consistency in variables and findings across studies an issue.
Chen et al (Chen *et al.*, 2009)	Systematic review. Sedentary lifestyle as a risk factor.	15 studies.	Sedentary lifestyle by itself is not associated with low back pain.
Fortin & Macedo (Fortin and Macedo, 2013)	Systematic review. Multifidus and paraspinal cross-sectional area.	11 studies.	Smaller cross-sectional area of paraspinal muscles (ES = -1.93 using weighted mean difference) and of multifidus muscle (ES = -1.67 using weighted mean difference) in those with low back pain.

ES – effect size, MRI – magnetic resonance imaging

5.2 Low back pain rehabilitation interventions

In an effort to improve outcomes for those with low back pain, a variety of rehabilitation interventions have been tested. Aerobic exercise, movement control, postural control, muscle strengthening, stretching and Pilates have all been recommended as possible treatments for those with low back pain (National Institute for Health and Care Excellence, 2009; Wells *et al.*, 2013). Given the large prevalence of low back pain and a need to better understand how to improve outcomes, a large variety of intervention studies related to the above intervention types have been completed. As such, systematic reviews exist for the majority of these intervention types and are listed in Table 22 (Hayden *et al.*, 2005; Mayer, Mooney and Dagenais, 2008; Macedo *et al.*, 2009; van Middelkoop *et al.*, 2011; Laird, Kent and Keating, 2012; Cramer *et al.*, 2013; Wells *et al.*, 2013; Stuber *et al.*, 2014; Smith, Littlewood and May, 2014; Steele, Bruce-Low and Smith, 2014b; Kamper *et al.*, 2015; Searle *et al.*, 2015; Saragiotto *et al.*, 2016; Vanti *et al.*, 2017)

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Hayden et al (Hayden, Tulder and Tomlinson, 2005) reviewed exercise therapies for low back pain and included data from 43 studies in an effort to understand the most effective structure of programs alongside the most effective exercise types. Strengthening, stretching, aerobic training, coordination and mobilising interventions were all included as part of the review with stretching and strengthening exercises found to be the most effective for alleviating and improving pain. Regarding program structure, it was suggested that programs should be individually designed, be of a high dosage (≥ 20 hours) and be regularly supervised in order to have the best possible outcome. Searle et al (Searle *et al.*, 2015) conducted a more recent review of exercise interventions and used a different method of categorising studies. They were divided into combined exercises, cardiorespiratory exercises, coordination/stabilisation and strength/resistance exercise. Significant effects were found for stabilisation (ES = -0.47) and strength training (ES = -0.50) alongside the more global conclusions that exercise interventions have a beneficial effect when compared to conservative therapies.

Advice to remain active is suggested as an adjunct to self-care and provision of evidence based information on low back pain in guidelines from the American College of Physicians and American Pain Society (Chou and Huffman, 2007). Remaining active can include aerobic activity such as walking, cycling or jogging which have been investigated as a treatment for low back pain. When considering aerobic training interventions in the literature, Hendrick et al (Hendrick *et al.*, 2010) reviewed walking interventions finding no evidence to support its use as a specific treatment for low back pain. In a systematic review and meta-analysis, Searle et al (Searle *et al.*, 2015) found no significant effect of cardiorespiratory exercise on low back pain. It is difficult to suggest a sound theoretical rationale for inclusion of aerobic training as an intervention for low back pain regardless of its effect. The primary adaptations to aerobic training are cardiovascular (Hellsten and Nyberg, 2016), a lack of which have not been suggested as a contributing factor for low back pain. It is possible that aerobic training has a psychological benefit in some participants which has been demonstrated elsewhere (Fuji *et al.*, 2009). These benefits have also seen in resistance training (O'Connor, Herring and Caravalho, 2010) meaning the psychological effects are not specific to aerobic exercise. It would appear that aerobic exercise is of limited benefit in treating low back pain.

Stretching is a common activity used as a method to alter muscular tension in order to increase range of motion about a joint. Hayden et al (Hayden, Tulder and Tomlinson, 2005) found that stretching exercises were the most effective intervention for reducing low back pain in their systematic review of exercise interventions. However, the link between lumbar range of motion and functional testing scores has been shown to be weak (Mannion *et al.*, 1999; Parks *et al.*, 2003). This might suggest that stretching effects something other than range of motion in order to reduce low back pain. In an intervention that looked at the short term effects of stretching on lumbar EMG activity, Solomonow et al (Solomonow *et al.*, 2003) observed later reduction in lumbar muscle activity during flexion and earlier activation during extension following ten minutes spent in standing end range lumbar flexion. Therefore, it is possible that, as a result of stretching, muscle activation patterns are altered contributing to reductions in pain. It has also been suggested that reductions in pain during exercise interventions may not necessarily be due to physiological adaptations but instead due to some central effect (Mannion *et al.*, 1999). It is known that fear avoidance beliefs are a factor in low back pain (Rainville *et al.*, 2011) and that lumbar flexion is altered as a result of higher levels of fear (Geisser *et al.*, 2004). Lumbar flexion based stretches may reduce the fear associated with flexion based movements and act to alter movement patterns reducing pain. Alternatively, for those who demonstrate the flexion or extension based patterns that have been associated with low back pain (O'Sullivan, 2005), spending time out of those postures during either flexion or extension based stretches may provide relief by reducing time spent in aggravating positions.

Pilates has been defined as a mind-body exercise technique aimed at core/abdominal stability, strength, flexibility, breathing and muscle control (Wells, Kolt and Bialocerkowski, 2012). There is a large amount of literature investigating Pilates in relation to low back pain, to the extent that Wells et al (Wells *et al.*, 2013) conducted a systematic review of systematic reviews of the effectiveness of Pilates exercise in treating those with low back pain. This review was carried out due to the lack of consensus among a number of systematic reviews on the effectiveness of Pilates. The conclusion reached was that there is inconclusive evidence that Pilates is effective in reducing pain and disability in people with chronic low back pain.

Alterations in biomechanical movement patterns have been demonstrated in those with low back pain when compared to healthy controls (Shum, Crosbie and Lee, 2005; Crosbie *et al.*, 2013). As a result, recommendations to restore normal function through exercise therapy have been made (Shum, Crosbie and Lee, 2007). However, in a review of biomechanical movement pattern modification based interventions, Laird (Laird, Kent and Keating, 2012) concluded that little difference exists between general exercise and specific interventions in their ability to alter activation of trunk musculature. The lack of quality trials that quantify the effect of interventions on muscle activity, lumbo-pelvic biomechanics or postural patterns was highlighted. Firm conclusions could not be drawn regarding lumbo-pelvic biomechanics and postural control as too few intervention studies exist. While evidence is lacking for the efficacy of interventions that specifically target biomechanical movement pattern modification, it is possible that alternative exercise interventions may alter those movement patterns. Further work is needed in order to understand if this is possible and the effect it has low back pain.

Strength training interventions have broadly been divided into two categories; isolated lumbar extensor strengthening and whole-body strengthening. Isolated lumbar extensor strengthening utilises loaded and unloaded lumbar extension exercises to increase the force output of the lumbar paraspinal musculature. These exercises can be performed using isokinetic dynamometers, variable resistance machines, benches, roman chairs or free-weights. The aims of using of such exercises are to alter the physiology of the lumbar musculature or to enhance metabolic exchange of the lumbar discs through repetitive movement (Mayer, Mooney and Dagenais, 2008). Steele et al (Steele, Bruce-Low and Smith, 2014b) conducted a review of isolated lumbar extensor training interventions finding consistent significant improvements within the 23 examined studies in measures of both pain and disability in response to isolated lumbar extensor training. Improvements were observed even with low volume and frequency (one set of an exercises once per week). Mayer et al (Mayer, Mooney and Dagenais, 2008) conducted an earlier review that included free-weight exercises, alongside machines, benches and roman chairs as a method of strengthening the lumbar extensors in those with low back pain. Overall, lumbar strengthening was suggested to be more effective on its own or with co-interventions than no treatment and most passive modalities. This type of strengthening improved pain, disability and other patient reported outcomes in those with low back pain. In their review, Mayer et al also suggest that dynamometers and Roman chairs are the best methods for achieving those gains in lumbar extensor strength and advise against the use of floor, stability ball and free-weight exercises. The reasoning behind this was that the movements are 'awkward' for patients, potentially unsafe, that it isn't possible to standardise load and they do not isolate the lumbar extensors. However, it appears from these reviews that lumbar extensor strengthening is beneficial in treating those with low back pain.

An alternative approach to isolated lumbar strengthening exercise is that of whole-body strength training. In this approach, muscle groups outside of just the lumbar extensors are targeted to increase an individual's all-round load tolerance. In one study, Maul et al (Maul *et al.*, 2005) utilised a twelve-week intervention utilising free-weights compared to a control group. They observed significant increases in strength and endurance (5 to 23%) and significant reductions in pain and disability (15 to 67%) in the intervention group with significant differences compared to the control group. Elsewhere, Kell & Asmundsen (Kell and Asmundson, 2009) compared the effectiveness of whole-body strength training using machine exercises and aerobic training in those with low back pain. Both groups trained three times a week for 16-weeks. The strength training group demonstrated significant improvements in pain, disability and quality of life (15 to 40%) alongside significant improvements in lumbar extensor and lower limb strength and endurance (13 to 28%). The Aerobic training group saw no significant improvements in pain, disability or quality of life. In a similar study design, Kell et al (Kell, Risi and Barden, 2011) investigated the effect of different strength training volumes in those with low back pain. They used the same exercises as Kell & Asmundsen (Kell and Asmundson, 2009) to design a 16-week program for four groups of sixty participants; a control, two sessions per week, three sessions per week and four sessions per week. All strength training groups demonstrated significant increases in the strength measures with more sessions per week resulting in greater strength gains. Pain reductions of 28%, 18% and 14% were seen in four, three and two sessions per week respectively, with a 2% reduction in the control group. Very similar patterns and percentage changes were seen in the disability and quality of life scores. This study demonstrated that higher volumes of strength training had a greater impact on increasing strength and reducing low back pain. From the same research, Jackson et al (2011) investigated the influence of periodisation in a low back pain rehabilitation program amongst recreationally active males. Three groups of participants formed a middle-aged intervention group (age = 52 ±2.7 yrs), an older aged intervention group (age = 63 ± 3.1 yrs) and a control group consisting of a mixed age group. The intervention consisted of the same machine base exercises as above but included some periodisation of the training intensity over the 16 weeks. The intensity increased from 55% 1RM early in the program up to 79% 1RM by the end with a reduced volume or ‘unload’ week every 4th week to allow some recovery. Significant improvements in pain, disability and quality of life scores were seen in both training groups with greater improvement seen in physical quality of life (31% vs 24%) in the middle-aged group and greater improvements in disability (52% vs 46%) and in the mental component of quality of life (27% vs 20%) in the older group. Similar reductions in pain of 26% and 27% were seen in the middle-aged and older aged groups respectively. This group of studies highlight the positive effect that whole-body strength training can have in reducing low back pain. While these data suggest that whole-body strength training can act to reduce pain and disability and improve quality of life in individuals with low back pain, it is difficult to say why exactly this is. The authors across the three studies suggest that the effectiveness of their strength training program was due to the focus being on the whole musculoskeletal system as opposed to solely core or lumbar strengthening. It is possible that an isolated lower body exercise, such as a leg extension which was used in the above studies, increases strength in the quadriceps allowing for them to take on more of the weight bearing tasks day to day. It is also possible that alterations to central neural drive associated with strength training (Gabriel, Kamen and Frost, 2006) altered recruitment patterns or that psychological changes seen following strength training (Vincent *et al.*, 2014) potentially reduced the catastrophizing behaviours associated with low back pain (O'Sullivan, 2005). Of interest is that whole-body strength training has shown greater efficacy in improving disability measures compared to isolated lumbar extension training (38% and 48% vs 20% and 11%) alongside greater reductions in pain catastrophizing (64% vs 31%) (Vincent *et al.*, 2014). The use of free-weight strength interventions are commonplace in the training of athletes and is considered effective in increasing strength, altering muscle structure and improving motor control (Haff, 2000). Deficiencies in these areas have been highlighted throughout this review as contributing factors in low back pain but interventions that utilise free-weight strength training are uncommon in the literature with only four studies found that utilise free-weight strength training (Holmberg, Crantz and Michaelson, 2012; Berglund *et al.*, 2014; Aasa *et al.*, 2015). One was a single participant pilot study using a deadlift exercise with one person with discogenic low back pain that showed no significant reductions in pain (Holmberg, Crantz and Michaelson, 2012). Two came from a larger trial involving two groups of 35 participants comparing low load motor control exercises with a deadlift intervention comprising of twelve training sessions over an eight-week period (Berglund *et al.*, 2014; Aasa *et al.*, 2015). They found that the higher the level pain and disability, the lower the likelihood of benefit from the deadlift training and that similar reductions in pain were seen in both groups (44% and 46%), but significantly greater improvement in patient functional outcomes was seen in the low load motor control group (110% vs 52%). Finally, in a two year follow-up to this study, there were no significant between group differences with both groups maintaining the pain reductions from the end of the intervention (Michaelson *et al.*, 2016). These studies used only one strength exercise, the deadlift, in their intervention which is different from the whole-body interventions discussed above. Further work is needed to determine if whole-body free-weight strength training is efficacious in the treatment of low back pain.

5.3 Conclusion

Low back pain is a prevalent condition with a wide variety of factors associated with its development. As such, a wide variety of approaches have been taken in an effort to treat it with varying results. The use of strength training has shown some promise with improvements observed through the use of both isolated lumbar extension and whole-body strength training approaches. The majority of the literature around both of these approaches utilises machine based interventions with very few studies utilising free-weight approaches commonly used in the strength training of athletes. Future work should aim to determine if such approaches are effective in treating low back pain.

Table 22: Review studies investigating low back pain rehabilitation interventions

Authors	**Study design**	**Studies**	**Results**
Searle et al (Searle *et al.*, 2015)	Systematic review and meta-analysis. Exercise for low back pain.	45 studies.	Small effect favouring stabilisation exercise (ES = -0.47 using Cohen's *d*) and resistance exercise (ES = -0.50 using Cohen's *d*). No significant effect of cardiovascular exercise or combined exercise.
Hayden et al (Hayden *et al.*, 2005)	Systematic review. Strategies for using exercise therapy.	43 studies.	Individually designed interventions delivered in a supervised setting with adherence to high dosage improve pain and function outcomes. Strengthening and stretching interventions were the most effective intervention types.
Van Middelkoop et al (van Middelkoop *et al.*, 2011)	Systematic review. Exercise therapy for low back pain.	83 studies.	No significant treatment effect for exercise compared to no treatment/waiting list controls. Pain and disability significantly reduced with exercise compared to usual care.
Cramer et al (Cramer *et al.*, 2013)	Systematic review and meta-analysis. Yoga for low back pain.	10 Studies.	Small positive effect for short term improvement in pain (ES = -0.48 using Cohen's *d*) and small positive effect for long term improvement in pain (ES = -0.33 using Cohen's *d*) for yoga.
Kamper et al (Kamper *et al.*, 2015)	Cochrane review. Biopsychosocial rehabilitation.	41 studies.	Small effect for multidisciplinary care having a greater effect over usual care for pain and disability (ES = 0.21 to 0.23 using Cohen's *d*). Small to moderate effect for

			multidisciplinary care displaying a greater effect over physical treatment, surgery and waiting list (ES = 0.25 to 0.73 using Cohen's *d*).
Macedo et al (Macedo *et al.*, 2009)	Systematic review. Motor control exercise for low back pain.	14 studies.	Motor control exercise is effective in reducing pain and disability in those with low back pain but is not more effective than manual therapy, surgery or other forms of exercise.
Saragiotto et al (Saragiotto *et al.*, 2016)	Cochrane review. Motor control exercise for low back pain.	29 studies.	Low quality evidence for a small but not clinically important effect for motor control exercise compared to other exercise in reducing pain and disability.
Vanti et al (Vanti *et al.*, 2017)	Systematic review and meta-analysis. Walking versus exercise.	5 studies.	Walking is not statistically inferior to exercise of higher intensity.
Laird et al (Laird, Kent and Keating, 2012)	Systematic review. Modification of movement patterns.	12 studies.	Non-significant changes in muscle activity patterns and no significant relationship with changes in pain.
Stuber et al (Stuber *et al.*, 2014)	Systematic review. Core stability exercises for athletes with low back pain.	5 Studies.	Most of the included studies reported statistically significant and clinically important improvements in pain intensity.

Wells et al (Wells *et al.*, 2013)	Systematic review of systematic reviews. Effectiveness of Pilates.	5 studies.	Inconclusive evidence that Pilates is effective in reducing pain and disability in those with low back pain.
Smith et al (Smith, Littlewood and May, 2014)	Systematic review and meta-analysis. Stabilisation exercises.	29 studies.	Clinically insignificant changes in pain and disability observed. No significant benefit in the long term for pain or disability compared with any other form of exercise.
Mayer et al (Mayer, Mooney and Dagenais, 2008)	Review. Lumbar extensor strengthening.	12 studies.	Lumbar extensor training by itself, or along with co-interventions is more effective than no treatment or passive treatments for improving pain and disability.
Steele et al (Steele, Bruce-Low and Smith, 2014b)	Review. Isolated lumbar extension training.	23 studies.	Consistent reductions in pain and disability were observed with high load (to muscle failure) and low frequency (once per week) appearing the most effective.

ES – effect size

6 General Methods

Many of the methods employed within this thesis were common throughout multiple studies. This section will outline those methods and the rationale for their selelction

6.1 Tests employed

The aim of this thesis is to explore the role of whole-body neuromuscular strength qualities in the rehabilitation of chronic musculoskeletal conditions and examine if the same qualities are important for performance. The neuromuscular strength qualities and their relevance for both rehabilitation and performance have been outlined above. This section will now discuss the selection of the tests used to measure those neuromuscular strength qualities.

6.1.1 Isometric mid-thigh pull

When considering maximum strength and explosive strength, the isometric mid-thigh pull (IMTP) is a commonly used tool for measurement of these qualities. It involves the participant standing on force plates and forcefully pulling upwards on a static bar creating an increase in ground reaction force. This force-time curve can then be analysed to calculate peak force and rate of force development (RFD) measures. This method was selected to allow interrogation of force-time data, alongside a relatively low level of technical proficiency required to complete the task, a factor that is affected by other maximum strength testing methods (Ritti-Dias *et al.*, 2011). In a recent systematic review of lower body multi-joint isometric tests from five isometric mid-thigh pull studies, Drake et al (Drake *et al.*, 2017) reported excellent intraclass correlation coefficients for between trials (0.80 to 0.99) well above the acceptable 0.7 level. While Drake et al suggested a lack of evidence available to ascertain criterion validity, they found strong evidence to support construct validity. The cohorts included in the review include both trained and untrained populations 18 to 30 years old suggesting that the measure is reliable across a range of populations. Elsewhere, other studies have observed excellent reliability in younger females (ICC > 0.87), male and female college athletes (ICC > 0.81) and elite athletes (ICC > 0.84) (Stone *et al.*, 2003; Beckham *et al.*, 2013; Moeskops *et al.*, 2018). However, due to logistical issues related to bringing participants into the clinic outside of rehabilitation sessions, it was not possible to conduct a reliability study with the isometric mid-thigh pull in those with low back pain or athletic groin pain. This perhaps may also explain why there appear to have been no previous reliability studies conducted on injured populations. However, given the high reliability demonstrated across a broad range of (non-injured) populations, the isometric mid-thigh pull was deemed a suitable measure to use within this thesis, although consideration should be given to the lack of dedicated injury-based reliability studies when interpreting the main findings of the study.

The test employed within this thesis utilised a customized set-up (Fittech, Australia) over two force plates (Figure 6). The height of the bar was set as the mid-point between the anterior superior iliac spine and the top of the patella measured while the participant stood with a knee flexion angle of around 140° measured with a goniometer. Grip was enhanced with the use of weightlifting wrist wraps. Participants familiarized themselves and warmed up by completing a pull at approximately 50%, 75% and 90% of their maximum effort. They then completed 3 trials of a pull and were instructed to keep their shoulders over the bar, look straight ahead and pull the bar vertically up as fast and hard as they could for 3 seconds. Participants had 30 seconds rest between each trial. Participants had 30 seconds rest between each trial.

Figure 6: Equipment set up for isometric mid-thigh pull test.

6.1.2 Single-leg squat jump

To obtain measures of explosive strength, the single-leg squat jump was selected. This was chosen over the bilateral version as between-limb analysis was required in one of the studies and maintaining consistency in this task was deemed important for interpretation of studies in relation to each other. A further reason for its selection was to allow analysis of accelerative ability by removing the eccentric component (Van Hooren *et al.*, 2017) which is utilised during the countermovement jump. Reliability for this measure has been demonstrated in an injured athletic male population (ICC > 0.93) (Lee *et al.*, 2018) and utilising a loaded version in healthy female and male athletes (ICC 0.88 to 0.91) (Kockum *et al.*, 2015). The test has been utilised elsewhere as part of a performance battery to assess concentric force production (Blache *et al.*, 2017; Vaisman *et al.*, 2017). Participants stood on one force plate with their hands on their hips, standing on their jumping leg and adopting a self-determined quarter squat position. They were instructed to stand still in the quarter squat position for 2 seconds then jump as high as possible, in as short a time as possible, without using a countermovement. Trials were repeated if they took their hands off their hips or were adjudged (from the vertical ground reaction force trace) to have utilised a countermovement to initiate the jump.

6.1.3 Single-leg drop jump

Reactive strength is a measure of an individual's ability to quickly move between an eccentric and concentric movement utilising the stretch shortening cycle (Young, 1995). It is commonly measured using the drop jump. Within this thesis, the use of a single-leg drop jump was employed to allow between-limb and intra-limb analyses. Reliability has been previously measured within the Sports Surgery Clinic laboratory, demonstrating good to excellent in injured populations (ICC 0.65 to 0.97) for kinetic measures. These findings are in line with reliability observed elsewhere in a non-injured population (ICC 0.7 to 0.9) for double leg versions of the drop jump (Beattie *et al.*, 2015). The single-leg drop jump was performed from a box (height 20cm) set at 2cm away from the force plates. Participants stood on their jumping leg with their hands on their hips and their toes over the edge of the box and were instructed to drop off the box, onto one of the force plates on the same leg and "jump as high as possible with as short a ground contact as possible, landing on two legs back on the force plates".

6.1.4 Single-leg drop landing

As a measure of deceleration, the single-leg drop landing was employed. Its use is commonplace in studies investigating injury (Doherty *et al.*, 2014; Ithurburn *et al.*, 2015; Pozzi *et al.*, 2017) but its relationship with cutting performance has yet to be investigated. It was selected for use within this thesis as it is an isolated task (i.e. no prior steps or jumps in the lead up to it) reducing variation in the movement and allowing a unilateral measure of deceleration. The single-leg drop landing has demonstrated greater reliability in ground reaction force variables (ICC > 0.97) than joint-based kinetic and kinematic variables (ICC 0.53 to 0.99) in non-injured recreational male and female athletes (Alenezi *et al.*, 2014). Elsewhere, good to excellent reliability (CMC 0.73 to 0.91) has been reported for joint kinetic and kinematic variables using a 30cm drop height in a non-injured female population (Myer *et al.*, 2016). Given the reliability observed and the common use of the task in understanding injury it was utilised in this thesis. During the single-leg drop landing, participants stood on their test leg with their hands on their hips and their toes over the edge of a 30cm box placed in front of the force plates. They were instructed to drop off the box onto the force plate landing on the same leg they were stood on and to absorb the landing as fast as possible and to hold the landing position for two seconds”.

6.1.5 Cutting tasks

As a measure of cutting performance two tasks were chosen; a 110° and a 45° cutting task. The layout of these tasks is shown in Figure 7. The 110° cut was chosen as it requires a deceleration to zero velocity in one plane of motion and a re-acceleration away from the cut. The aim of the 45° cut was to emphasize a more accelerative demand. This was achieved by limiting the distance in the approach and selecting an angle whereby zero velocity in one plane is not reached. Reliability of the 110° cut has previously been demonstrated to be fair to excellent in a non-injured male cohort (ICC = 0.4 to 0.91) within the Sports Surgery Clinic biomechanics laboratory (Marshall *et al.*, 2014). Similar 45° cuts have demonstrated good to excellent reliability in non-injured male and female athletes (ICC 0.71 to 0.99) (Spiteri, Hart, *et al.*, 2014; Spiteri, Nimphius, *et al.*, 2014; Rouissi *et al.*, 2016).

The procedure for the 110° change of direction task has been described elsewhere (Marshall *et al.*, 2014) with the addition of timing gates (Fusion Sport Smartspeed, Queensland, Australia) at two metres before and after the force plates. The timing gates were set 1.5 metres apart at a height of 1.2 metres (Figure 19A). The 45° change of direction had the same timing gates set 2 metres before the force plates and two metres on the far side at an angle of 45° from the centre of the plates and the midline between the timing gates (Figure 19B). Participants started 30cm behind the first timing gate in a staggered stance. The 2 metre distance before the plate was selected as it allowed for only one foot-contact prior to the change of direction limiting variability in technique prior to the cut. Participants were instructed to complete the task as fast as possible and were asked to repeat the task if they took a step backwards prior to moving forwards and if a full contact with the force plate wasn’t achieved.

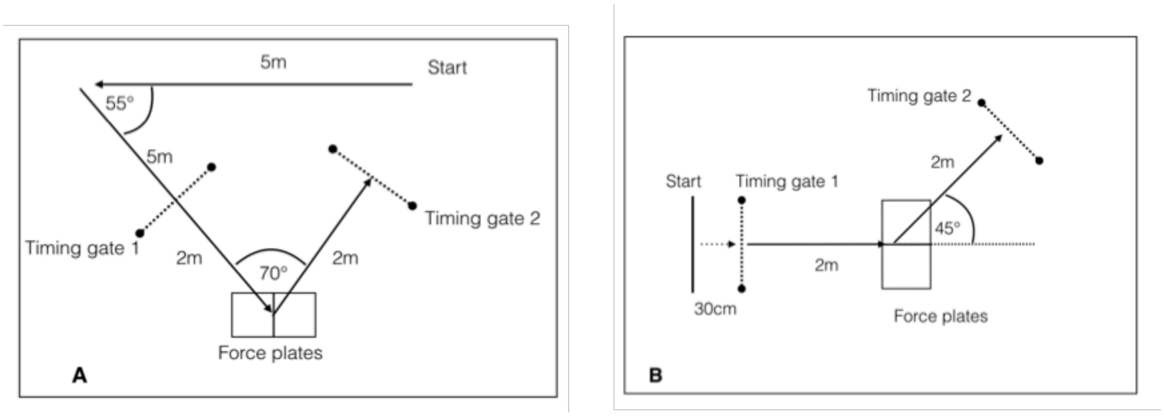

Figure 7: Layout for the A) 110° cut and B) the 45° cut

6.2 Data analysis

6.2.1 Principal component analysis

Two data analysis approaches were included across chapters eight to eleven. These were utilised to address issues with more commonly employed biomechanical analyses. When performing an exploratory analysis there are a large number of variables that can be assessed. These include ground reaction force measures and joint based kinetic and kinematic variables in all three planes (giving rise to approximately 100 variables), many of which correlate with each other. This creates difficulty for the practitioner in interpreting the data and being able to apply the findings to an athlete through intervention. An example of this can be observed in the study by Edwards et al (Edwards *et al.*, 2017). The results highlight between-group differences at three different time-points during a cut creating a total of forty-five variables for the reader to interpret. A solution to this issue is to employ a principal component analysis (PCA), which is a dimension reduction technique that groups variables together by patterns of common variation. It therefore allows a movement technique to be explained by a significantly reduced number of principal components rather than by tens of (possibly related) variables. This approach has been employed elsewhere within biomechanics in the analysis of jumping tasks (Harrison *et al.*, 2007) and was suggested as a tool useful for quantifying trends in movement coordination.

6.2.2 Monte Carlo simulation

Another issue with biomechanical analysis is related to the selection of trials for analysis. For example, if three trials of a task are completed, it is commonplace to calculate a mean of the three trials for analysis. This approach has been taken within the cutting biomechanics literature (Dempsey *et al.*, 2007; Marshall *et al.*, 2014). This assumes however, that the mean of the trials is representative of the all the trials captured and also that the mean of the trials could exist in reality. This approach discards all of the actual trials recorded. Another approach to negate this issue would be to select a trial based on the highest performing trial as determined by a single variable. This, however, again would assume that the selected trial was representative of all of the movements produced by the individual. This could bias the analysis towards a movement that is not representative whilst also discarding the rest of the captured data. Further, another common approach is to use only the dominant limb in the analysis (Marshall *et al.*, 2014; Havens *et al.*, 2015). This approach creates difficulty in terms of how to determine dominance which is possible to do by preferred kicking foot, preferred jumping leg or strongest leg to name but a few options. An alternative strategy to address these issues was used throughout this thesis in chapters eight to eleven, a random sampling approach called Monte Carlo simulation, which will be referred to as 'simulation'. This is where a trial is selected at random out of all the trial on either leg for each participant. A between-group or correlation analysis, depending on the study, was then performed with the result saved. This was the first simulation. This process of random selection then analysis is repeated for multiple simulations. Within this thesis, 100 simulations were used for each analysis and a cutoff of 95% set to denote relevance/significance of a principal component. For example, in the correlation analysis, if the direction of the correlation was either positive or negative for 95% or greater of the simulations, then the variable was deemed relevant/significant. This method also allows for trials from both limbs to be used, includes all of the captured trials, only uses trials that were actually recorded instead of a mean and also increases the sample size used for analysis. For example, if 25 participants were included, and each participant performed 3 cuts on each leg, the simulation approach utilizes all 150 measured cuts for analysis. By taking a mean of the cuts or selecting the fastest one, and only utilising one limb for analysis, the testing sample is reduced to only 25. This form of analysis has recently been used elsewhere in biomechanical analysis (Richter, King, *et al.*, 2018; Richter, O'Malley, *et al.*, 2018). While these methods were adopted with the aim of addressing the issues with exploratory biomechanical analyses, it is important to acknowledge possible limitations. A principal component analysis uses variation within data to group biomechanical variables. While, this grouping best describes data in respect to variability it may not best describe the dependent variable. Further, it is possible that groups or clusters of data exist within a single principle component. A principle component analysis is unable to recognize these clusters. In addition, with respect to the simulation analysis, the random selection of tasks assumes a relatively even selection. However, if by chance, a single trial is selected with a high frequency, there is a possibility of skewing the analysis. In an effort to address the issues with exploratory biomechanical analysis described above, this simulation approach has been adopted for chapters eight to eleven.

7 The effects of a free-weight based resistance training intervention on pain, squat biomechanics and MRI-defined lumbar fat infiltration and functional cross-sectional area in those with chronic low back pain

Welch, N, Moran, K, Antony, J, Richter, C, Marshall, B, Coyle, J, Falvey, E and Frankly-Miller, A (2015). The effects of a free-weight based resistance training intervention of pain, squat biomechanics and MRI-defined lumbar fat infiltration and functional cross-sectional area in those with chronic low back pain. BMJ open sport and exercise medicine. 1(1) pp. 1-10.

7.1 Introduction

Chronic low back pain is a prevalent musculoskeletal diagnosis affecting a broad range of ages and educational and income levels; a mean prevalence rate of 18.1% has been reported in the literature (Hoy *et al.*, 2010). Existing classification systems demonstrating the wide range of possible symptoms highlight the complexity of the condition and offer a method of categorising patients by pathology and or psychological and social factors (Spitzer, 1987).

In low back pain cases where surgery is not appropriate, genetic, psychological, social and physical factors need to be considered as part of a bio-psychosocial approach to treatment (O'Sullivan, 2005). When considering physical factors, exercise interventions have been recommended as a conservative treatment (Chou *et al.*, 2007; National Institute for Health and Care Excellence, 2009). In instances where pathology results in neurological deficit or pain, surgical intervention may be considered. These interventions include fusion for low back pain due to disc degeneration, discectomy for radicular symptoms due to disc herniation or bulging and laminectomy for symptomatic stenosis (Chou *et al.*, 2009). Another treatment for radicular symptoms is transforaminal steroid injection which has mixed outcomes (Macvicar, King and Landers, 2013).

Multiple non-surgical interventions are described (Last and Hulbert, 2009). It has been suggested that resistance training is an effective intervention that may obviate the requirement for injection or surgery. The evidence for resistance training in musculoskeletal rehabilitation (Kristensen and Franklyn-miller, 2012) demonstrates greater effectiveness than aerobic, coordination, mobilisation or Pilates training (Hayden, Tulder and Tomlinson, 2005; Wells *et al.*, 2013). Resistance training can be used to train maximum strength and endurance, both of which have been associated with the development low back pain (Steele, Bruce-Low and Smith, 2014a).

Compensatory motor patterns have been associated with chronic low back pain during completion of sit to stand tasks (Shum, Crosbie and Lee, 2007). It is recommended that treatments seek to restore normal kinetic and kinematic characteristics. It has also been demonstrated that individuals with low back pain and greater pain-related fear change movement patterns in an effort to reduce lumbar spine motion during some tasks (Thomas and France, 2007). While the use of resistance training may alter the fear-related aspects of low back pain (Vincent *et al.*, 2014), limited support has been presented for the ability of rehabilitation interventions to change movement patterns (Laird, Kent and Keating, 2012). No research into the effects of free-weight resistance training on biomechanics in those with low back pain could be found.

It is common for those with low back pain to undergo Plain X Ray imaging, Computerised Tomography or Magnetic Resonance Imaging to delineate anatomical pathology (Mitchell, 2008). Magnetic Resonance Imaging (MRI) provides accurate imaging of disk and neural tissue, bony stress and other soft tissue, in particular, muscle. Higher levels of MRI-defined lumbar fat infiltration and smaller paraspinal cross sectional areas have been observed in those with LBP (Mengiardi *et al.*, 2006; Kjaer *et al.*, 2007; Pezolato *et al.*, 2012; Fortin and Macedo, 2013). This muscular atrophy occurs through a number of different cellular and molecular pathways and can be caused by inactivity (Wiggs, 2015). Willemink et al published the sole study examining alterations in MRI defined lumbar fat infiltration following training (Willemink *et al.*, 2012). No significant muscle structure changes were seen.

The use of free-weight exercises is commonplace in the training of athletes and is considered effective in increasing maximum strength, explosive strength and endurance, altering muscle structure and improving motor control (Haff, 2000). Despite deficiencies in these areas having been linked to low back pain (Shum, Crosbie and Lee, 2007; Steele, Bruce-Low and Smith, 2014a; Rossi *et al.*, 2017), the use of free-weight resistance training in the rehabilitation of those with low back pain is limited. It is known that resistance training can alter muscle composition and illicit high levels of lumbar erector and other posterior chain muscle activity (Schoenfeld, 2010; Swinton *et al.*, 2012). However, it is unknown what effect a free-weight resistance training intervention has on MRI defined lumbar fat infiltration, biomechanics and pain in those presenting with low back pain.

The aim of the current study is to examine the effects of a free-weight based progressive resistance training intervention on pain, disability, quality of life, MRI-defined lumbar fat infiltration and functional cross-sectional area (FCSA), squat biomechanics and maximum strength and endurance in those with chronic low back pain. It is hypothesised that a significant reduction in low back pain will be observed alongside a significant increase in maximum strength and endurance.

7.2 Methods

Participants had presented with low back pain to one of 6 Sports Physicians at a large sports medicine practice. All subjects underwent clinical history and examination by a Sports Physician including MRI examination. The symptoms had been present for greater than 3 months, with or without radicular pain. Exclusion criteria were: previous spinal surgery, tumors, nerve root entrapment accompanied by neurological deficit, spinal infection, inflammatory disease of the spine and other disorders preventing active rehabilitation. Those who met the inclusion criteria were informed of the study, given an information leaflet and offered the opportunity to ask questions of the lead researcher. All participants completed and signed an informed consent form prior to partaking; the study met the approval of the Sports Surgery Clinic Hospital Ethics committee (25-EF-008). Thirty participants, 11 females (age = 39.6 ± 12.4 years, height = 164 cm ± 5.3cm, body mass = 70.9 ± 8.2kg,) and 19 males (age = 39.7 ± 9.7 years, height = 179 ± 5.9cm, body mass = 86.6 ± 15.9kg,) between the ages of 16 and 60 were recruited. Four participants dropped out due to: an unrelated ankle injury (n = 1), not attending all testing sessions (n = 1), work commitments (n = 1) and a lack of adherence to the program (n = 1).

On entering the laboratory, participants were asked to fill out disability, pain and quality of life questionnaires; the Oswestry Disability Index (ODI); Visual Analogue Scale (VAS); and a Euro-QOL-5D Version 2 (Euro-Qol) questionnaire were used respectively. A flow chart of the three testing sessions, questionnaires and training can be seen in **Error! Reference source not found.** and Figure 9. An 8-camera m otion analysis system (Bonita B10, Vicon, UK), synchronised with two 40 x 60 cm force platforms (BP400600, AMTI, USA) was used to collect kinematic and kinetic data for all tests. Data was sampled at 200Hz and the Vicon Plug-in-Gait marker set was used as per Marshall et al (Marshall *et al.*, 2014).

Week 1: VAS, ODI and Euro-qol, 3D testing, MTP, Biering-Sorensen test.
Addressing of beliefs, coaching of lumbo pelvic control and individualised postural adjustments (i.e.moving from sway back to neutral, from active extension to neutral and relaxed while sitting and standing). Start of 4 week familiarisation phase: Session 1 of single-leg gluteus raise, goblet squats, split squats, planks and standing row exercises. Load approx 10RM, 3 sets of 8, 3 sessions per week

Week 2: Delivery of session 2: Standardised warm up (gluteus self myofascial release, glute raise, multi direction lunge, standing hamstring stretch to overhead squat, assisted squat), deadlifts, step ups, lat pulldown, sid bridge, press up. Sessions alternated between 2 x session 1 and 1 x session 2 in one week and 1x session 1 and 2 x session 2 in the following week.

Week 4: VAS, ODI and Euro-qol, MTP, 3D testing and Biering-Sorensen. Start of strength phase. One coached session to demonstrate loading changes to approx 6-7RM 3 sets of 5, 3 sessions per week

VAS, ODI and Euro-qol questionnaires taken every **4 weeks**, supervised session once every **2 weeks**

Week 16: VAS, ODI and Euro-qol questionnaires, repeat MRI, MTP, 3D testing, Biering Sorensen

Figure 8: Flow chart of the experimental design. MTP – mid-thigh pull, VAS – visual analogue scale, ODI – Oswestry disability index, MRI – magnetic resonance imaging

Ankle, knee, hip, pelvis and thorax angles and internal joint moments at the hip knee and ankle were calculated throughout the movement in all three planes. Angles were normalised to a standing static trial (Hamill, Selbie and Kepple, 2014). A continuous waveform analysis, Analysis of Characterising Phases (ACP) (Richter *et al.*, 2014), was conducted to examine differences between the measurements. Before performing ACP, waveforms were landmark registered to the start of the concentric phase. This was done to remove temporal variations in the start of the concentric phase (Ramsay, 2006) between the subjects. Subsequently, ACP was applied to generate Subject Scores to describe a subject's behavior over key phases (phases of variation). Subject scores were tested for significant differences using an ANOVA. If subject scores differed within a key phases, phases were extended to discover the full phase of significant difference (Richter *et al.*, 2014).

Warm up: Participants completed a warm up of five bodyweight squats and two forward, backward and lateral lunges on each leg prior to testing.

Squat movement testing: Testing involved three trials of a bodyweight bilateral squat. Participants were asked to keep their heels on the ground going down as far as they could go comfortably with a maximum depth of thigh parallel to the ground

Isometric mid-thigh pull testing: Bar height was set by measuring the mid-point between the top of the patella and the anterior superior iliac spine and the distance from that point while standing up straight to the ground. Participants familiarised themselves by completing a pull at approximately 50%, 75% and 100% of their maximum effort. They then completed 3 trials of a pull and were instructed keep their shoulders over the bar, look straight ahead and pull the bar up as fast and hard as they could for 3 seconds. They had 15 seconds break between each trial.

Figure 9: A flow chart of the biomechanical testing.

A Biering-Sorensen test was used to measure back extension endurance (Biering-Sorensen, 1984). The patient lay on the examining table in the prone position with the upper edge of the iliac crests aligned with the edge of the table. The lower body was fixed to the table by two straps, located around the pelvis and mid-calf. With the arms folded across the chest, the patient was asked to isometrically maintain the upper body in a horizontal position (Figure 10). The time during which the patient kept the upper body straight and horizontal was recorded. This test has demonstrated good to excellent test-retest reliability (Latimer *et al.*, 1999).

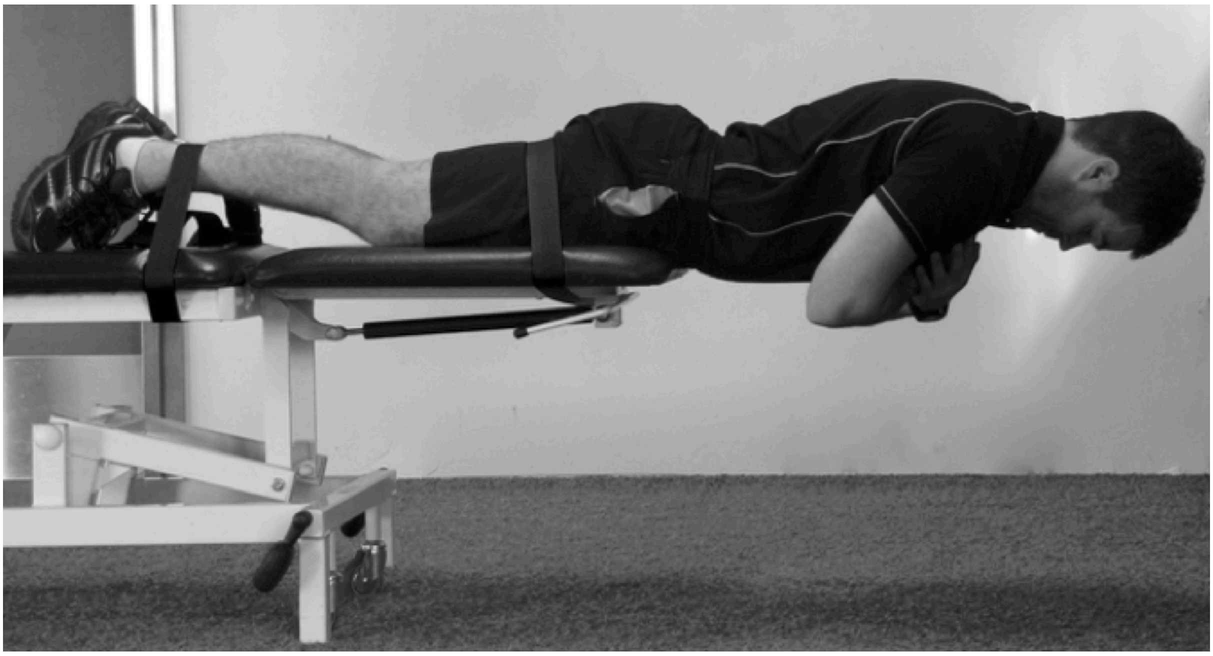

Figure 10: Positioning for Biering Sorensen back endurance test.

Isometric mid-thigh pull tests were completed using a custom set up with the laboratory force plates (Fit-tech, Australia, Figure 11). This was used to assess maximum strength and explosive strength. Testing protocol can be seen in Figure 9. The isometric mid-thigh pull was not included in the first testing session as a maximum isometric strength test was deemed inappropriate in an initial testing battery for those with low back pain. Vertical ground reaction force data from both force plates were summed. The start of the isometric mid-thigh pull was defined as the point at which vertical force first passed 1.2 x bodyweight. Peak force was identified as the point at which ground reaction forces reached a maximum. Rate of force development was calculated by dividing force by the time over which force was applied. Rate of force development was calculated to peak force and over the first 50ms, 100ms, 250ms and 500ms. Peak force and rate of force development measures were then normalised to body weight (N/kg^{-1}).

Figure 11: Equipment set up for isometric mid-thigh pull test.

Lumbar spine Magnetic Resonance Images (MRIs) were obtained at initial clinical assessment on entering the study (Table 23) and following intervention. These were used to measure fat infiltration and functional cross sectional area of the lumbar paraspinal musculature. The majority of images were obtained using a 3 Tesla MRI system (GE Signa, General Electric Healthcare, USA). Five participants provided images completed on a 1.5 Tesla MRI system. Axial T2 weighted non-fat-saturated sequences were used for evaluation. Fat infiltration and, where possible, FCSA (defined as the fat free area) was measured at the lower end plate at the L3L4, L4L5 and L5S1 levels. The region of interest was defined as the area of erector spinae and multifidus musculature (Lee *et al.*, 2008; Kong, Lim and Kim, 2014) and percentage fat infiltration was calculated for the total area using a standalone graphical user interface developed in Matlab R2010a (Antony *et al.*, 2014) (Figure 12). A methodological study was undertaken that demonstrated greater sensitivity to change in fat-infiltration using such a computer based quantitative approach compared to visual qualitative techniques (Appendix 1: A comparison of quantitative computer base and qualitative visual analysis techniques for measuring changes in MRI-defined lumbar fat infiltration). Intra-user reliability in selecting the region of interest and changes in signal intensity was tested using sixty images on two occasions, two days apart.

Table 23: A list of radiology reported MRI diagnoses on entering the study at L3L4, L4L5 and L5S1 levels and the number of times they were reported across all participants.

Reported finding	**Number of times reported**
Disk herniation without nerve compression	33
Disk herniation with nerve compression	11
Disk desiccation without herniation	1
Modic changes	2
Facet joint degeneration	20

Disk herniation includes reported: disk prolapses, disk protrusions, disk bulges, annular disk tears and annular fissures with or without a reported nerve compression. Facet joint degeneration includes reported degeneration and facet joint osteophyte formations.

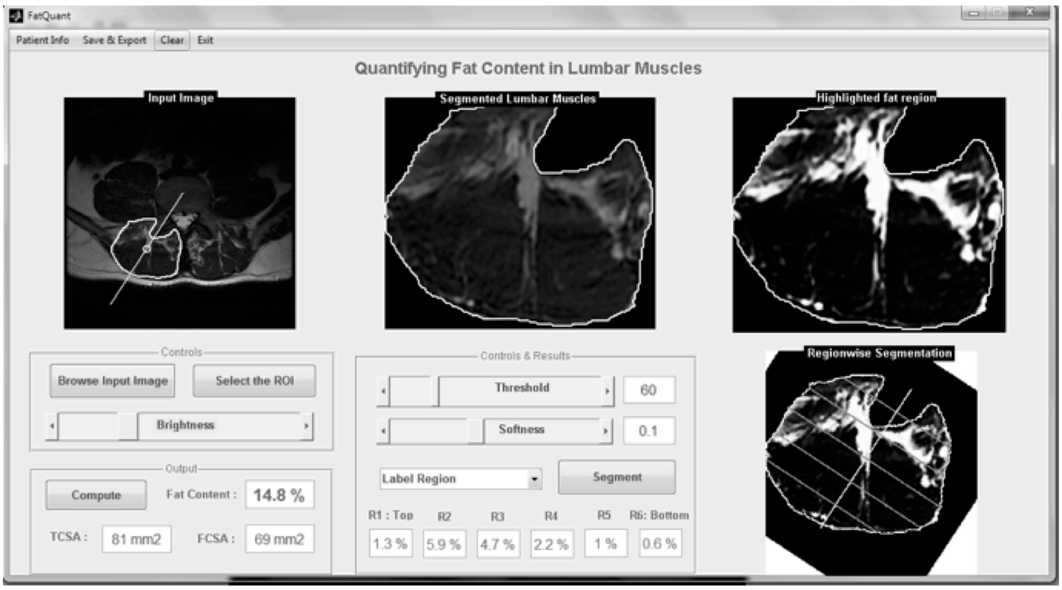

Figure 12: Screenshot of the Graphical User Interface used to calculate fat infiltration.

After initial testing, participants were instructed regarding their training program. During a 1-hour gym session, participants were firstly asked to explain their beliefs around the causes of their pain to address psychosocial aspects that are a component of low back pain (Waddell, 2004). Any areas where it was felt that their beliefs were contributing towards their back pain were addressed (Table 24). The exercises were delivered across two sessions (**Error! Reference source not found.**). The 10RM and 6-7RM loads were estimated by the participant and adjusted where necessary at the end of each set. Emphasis in each of the exercises was placed on maintaining a neutral lumbo-pelvic position. In participants who were unable to prevent lumbar flexion when deadlifting off the floor, the bar was raised to a level in a squat rack where a straight back could be maintained. Participants were given a booklet containing their training program and recorded missed sessions by crossing them out. Reported adherence was high with a mean of 2.1 missed sessions from a possible 48.

Table 24: List of participant beliefs regarding their back the education they received

Belief	**Education**
Keeping their spine straight is better for their back	Informed that there is no issue with moving into lumbar flexion and that spine has evolved to be able to do that
Their disc bulge is causing their pain	Informed that the link between non-specific chronic low back pain and MR findings is thin
They need to protect their back to prevent damage	The guarding patterns like bracing and breath holding is interfering with movement patterns and that nothing bad will happen if they don't brace their abdominals while moving. Pain doesn't mean damage
Certain movements/tasks e.g. squatting cause pain and shouldn't be done	Informed that it's not the activity but how they're doing it that is causing their pain. Demonstrated throughout the training
Lifting weights is bad for their back	Came from the first session where they lifted weights with no increase in pain

Participants were filmed (iPad 3, Apple inc) completing their exercises with a commentary of the coaching points and given access to those videos online using Dartfish video analysis software (Dartfish, USA). Externally focused coaching cues were used to maximise skill acquisition and learning (Wulf, Shea and Lewthwaite, 2010); these are listed in Table 25: A list of resistance exercises and coaching cues used. Outcome measures of interest were pain VAS, ODI and Euro-Qol, peak vertical ground reaction force during isometric mid-thigh pull, lumbar extensor time to exhaustion, percentage fat infiltration and cross-sectional area of lumbar paraspinals at L3L4, L4L5 and L5S1 levels, and sagittal plane kinetic and kinematic variables about the ankle, knee, hip and torso throughout a bodyweight squat.

Table 25: A list of resistance exercises and coaching cues used

Exercise	**External focus of attention**
Lumbo pelvic control	Belt buckle pointing to the horizon, not at the floor
Goblet squat	Bum goes back as if towards a chair, belt buckle up at the top
Deadlift	Bum goes back as if towards a chair, belt buckle up at the top
Split squat	Belt buckle up, push through heel of the front foot
Step up	Push the foot hard into the step, get up as fast as possible, opposite heel to hamstring at the top
Plank	Belt buckle up, if you feel it in your back you’re doing it wrong
Side bridge	Keep your body in a straight line
Press up	Push up so that your whole-body leaves the ground at the same time. Belt buckle up
Lat pulldown	Sit on the top of your glutes, pull the bar to your chest
Standing row	Belt buckle up, keep you elbow low against your side

Statistical Analysis

All values were reported as mean, SD and 95% confidence interval (for parametric data) (mean ± SD [CI]), and percentage change following intervention. All data were checked for normality using a Shapiro-Wilk test. Differences in all outcome measures for the Biering-Sorensen endurance test between pre-, week four and post-intervention were assessed using a repeated measures one-way ANOVA with Bonferroni adjusted post-hoc pair-wise comparison. Differences in isometric mid-thigh pull scores, fat infiltration and functional cross sectional area were assessed using paired samples T-test. Differences in Oswestry disability index, visual analogue scale and Euro-QOL data were assessed using a Wilcoxon-Signed rank test. A p level of < 0.05 was adopted for statistical significance. Intra-class correlation coefficients were used to examine intra-user (ICC [3, 1]) reliability of measuring lumbar fat infiltration. The ICC classifications of Fleiss (Fleiss, 1986) were used to describe the range of ICC values where less than 0.4 was poor, between 0.4 and 0.75 was fair to good, and greater than 0.75 was excellent. All statistical analyses were performed using IBM SPSS (version 21; IBM, New York, NY, USA).

7.3 Results

The participants showed significant improvement in the Oswestry disability index (ODI) at weeks 4 ($Z = -3.84$, $p < 0.001$) and 16 compared to baseline ($Z = -4.46$, $p < 0.001$), pain visual analogue scale (VAS) at weeks 4 ($Z = -3.75$, $p < 0.001$) and 16 compared to baseline ($Z = -4.46$, $p < 0.001$) and Euro-Qol scores at weeks 4 ($Z = -2.98$, $p = 0.03$) and 16 ($Z = -3.97$, $p < 0.001$) compared to baseline (Table 26). The Biering-Sorensen test scores showed significant increases in lumbar endurance between baseline and week 16 ($F(1.80,43.1) = 5.04$, $p < 0.05$). No significant improvement ($p = 0.08$) was seen in maximum strength.

Significant reductions in percentage fat infiltration were seen bilaterally at L3L4 and L4L5 levels from pre to post intervention ($t(24) = 2.45$ to 4.6; 15% to 32% reductions) (Table 27). No significant changes were seen at the L5S1 level. Significant increases in FCSA were seen bilaterally at L3L4 and L4L5 levels from pre to post intervention ($t(14) = -4.3$ to -2.2; 1.9% to 3.8% increases) (Table 28).

The ICC was calculated at 0.97 giving an excellent level of intra-user reliability (Fleiss, 1986).

Significant increases in centre of mass vertical velocity, sagittal plane pelvis tilt angle, hip flexion angle, knee moment and hip moment were evident in the waveforms (figures 11-15). No significant differences in sagittal plane ankle, knee, thorax and thorax to pelvis angles were seen.

Table 26: Pain, disability, quality of life, maximum strength, explosive strength and endurance

	Mean ± SD			***d***		
	Baseline	**4 Weeks**	**16 Weeks**	**0-4**	**0-16**	**4-16**
VAS	4.5 ± 2.2	2.8 ± 1.6	1.3 ± 1.4	0.45*	0.89*	0.5*
ODI	22.9 ± 1.2	13.4 ± 9.1	5.4 ± 5.7	0.92*	2.54*	0.54*
Euro-Qol	0.7 ± 0.2	0.8 ± 0.12	0.9 ± 0.1	-0.31*	-0.67*	0.45*
PF ($N.kg^{-1}$)		23.5 ± 4.3	24.1 ± 4.7			0.07
RFDpeak ($N.s^{-1}$)		38.6 ± 36	34.6 ± 41			0.05
RFD50 ($N.s^{-1}$)		303 ± 63	301 ± 52			0.02
RFD100 ($N.s^{-1}$)		170 ± 36	171 ± 30			0.02
RFD250 ($N.s^{-1}$)		83 ± 17	84 ± 17			0.03
RFD500 ($N.s^{-1}$)		45 ± 9	45 ± 9			0
BS (s)	89 ± 43	94 ± 38	104 ± 41	-0.06	-0.18*	-0.13

*VAS – visual analogue scale, ODI – Oswestry disability index, IMTP – isometric mid-thigh pull, BS – Biering-Sorensen back extension endurance test, RFDpeak – rate of force development to peak force, RFD50/100/250/500 – rate of force development over the first 50ms, 100ms, 250ms and 500ms. * indicates significant differences (p ≤ 0.05). d –* Cohen's d

Table 27: Mean Percentage fat infiltration ± SD [95% CI] of the lumbar paraspinal muscles pre- and post-intervention.

L3L4	**Left pre (%)**	**Left post (%)**	***d***	**Right pre (%)**	**Right post (%)**	***d***
Total	13.0 ± 8.2 [9.8-16.2]	10.0 ± 6.3 [7.56-12.46]	0.21*	12.1 ± 6.1 [9.7-14.5]	9.4 ± 5.3 [7.3-11.5]	0.24*
R1	2.8 ± 1.1 [2.3-3.2]	2.1 ± 1.2 [1.7-2.6]	0.30*	2.6 ± 0.9 [2.2-2.9]	2.2 ± 1.2 [1.7-2.6]	0.19*
R2	2.8 ± 2.1 [2.0-3.6]	2.3 ± 2.1 [1.5-3.1]	0.12*	2.3 ± 1.6 [1.7-3.0]	1.8 ± 1.3 [1.3-2.3]	0.17*
R3	2.3 ± 2.2 [1.4-3.2]	1.7 ± 1.4 [1.1-2.2]	0.17*	2.2 ± 1.7 [1.5-2.8]	1.7 ± 1.3 [1.2-2.2]	0.17*
R4	1.7 ± 1.6 [1.1-2.3]	1.2 ± 0.9 [0.9-1.5]	0.20*	1.8 ± 1.5 [1.2-2.4]	1.3 ± 0.9 [1.0-1.7]	0.21*
R5	2.1 ± 1.3 [1.5-2.6]	1.6 ± 1.1 [1.1-2.0]	0.21*	2.1 ± 1.3 [1.6-2.6]	1.5 ± 1.0 [1.1-1.9]	0.26*
R6	1.7 ± 1.1 [1.2-2.1]	1.4 ± 1.1 [1.0-1.8]	0.14	1.6 ± 1.0 [1.2-2.0]	1.2 ± 1.0 [0.8-1.6]	0.2*

L4L5	**Left pre (%)**	**Left post (%)**	***d***	**Right pre (%)**	**Right post (%)**	***d***
Total	14.3 ± 7.0 [11.6-17.1]	11.8 ± 6.0 [9.4-14.1]	0.19*	13.6 ± 5.6 [11.5-15.8]	11.7 ± 5.6 [9.6-13.9]	0.17*
R1	3.3 ± 1.2 [2.8-3.7]	2.8 ± 1.4 [2.3-3.8]	0.19	3.0 ± 1.0 [2.6-3.4]	3.2 ± 1.4 [2.7-3.8]	-0.08
R2	4.1 ± 2.2 [3.3-5.0]	3.7 ± 2.3 [2.8-4.6]	0.09	3.6 ± 1.9 [2.9-4.4]	3.1 ± 2.0 [2.3-3.9]	0.13*
R3	2.6 ±1.5 [2.0-3.2]	2.0 ± 1.6 [1.4-2.6]	0.19*	2.6 ± 1.9 [1.9-3.4]	2.2 ± 1.8 [1.5-2.9]	0.11*
R4	1.7 ± 1.3 [1.2-2.2]	1.4 ± 1.1 [1.0-1.8]	0.13*	1.9 ± 1.6 [1.3-2.5]	1.5 ± 1.3 [1.0-2.0]	0.14*
R5	1.6 ± 1.2 [1.1-2.1]	1.1 ± 0.8 [0.8-1.4]	0.25*	1.6 ± 1.1 [1.2-2.0]	1.1 ± 0.7 [0.8-1.4]	0.28*
R6	1.7 ± 1.0 [1.3-2.1]	1.2 ± 0.8 [1.0-1.5]	0.28*	1.8 ± 1.1 [1.3-2.2]	1.3 ± 0.8 [1.0-1.7]	0.26*

L5S1	Left pre (%)	Left post (%)	*d*	Right pre (%)	Right post (%)	*d*
Total	18.0 ± 5.9 [15.7-20.3]	17.3 ± 7.0 [14.6-20.1]	0.05	17.8 ± 6.2 [15.4-20.3]	16.3 ± 7.2 [13.5-19.1]	0.11
R1	4.1 ± 1.6 [3.4-4.7]	3.9 ± 1.7 [3.2-4.5]	0.06	4.1 ± 1.3 [3.6-4.6]	3.9 ± 1.4 [3.4-4.5]	0.07
R2	6.3 ± 2.0 [5.6-7.1]	6.1 ± 2.4 [5.2-7.1]	0.05	5.4 ± 2.1 [4.6-6.3]	5.3 ± 2.6 [4.3-6.3]	0.02
R3	4.2 ± 2.3 [3.3-5.1]	4.1 ± 2.3 [3.2-5.0]	0.02	4.2 ± 2.2 [3.4-5.1]	3.7 ± 2.5 [2.8-4.7]	0.11
R4	2.4 ± 1.6 [1.8-3.1]	2.2 ± 1.5 [1.6-2.8]	0.06	2.5 ± 1.5 [2.0-3.1]	2.0 ± 1.8 [1.3-2.8]	0.15
R5	1.2 ± 0.8 [0.9-1.5]	1.3 ± 1.2 [0.8-1.8]	-0.05	1.5 ± 0.9 [1.2-1.9]	1.2 ± 1.1 [0.8-1.7]	0.15*
R6	1.4 ± 0.9 [1.0-1.7]	1.3 ± 1.3 [0.8-1.8]	0.05	1.4 ± 0.8 [1.1-1.7]	1.3 ± 1.2 [0.8-1.8]	0.05

** Significant difference ($p \leq 0.05$) between baseline and week 16. R1-R6 are the regions away from the centre of the spinal cord where region 1 is closest and region 6 furthest. d – Cohen's d*

Table 28: Functional cross-sectional area (mm2) ± SD [95% CI] of the 15 participants who had pre and post MRIs.

Lumbar level	**Left pre**	**Left post**	***d***	**Right pre**	**Right post**	***d***
L3L4	85.8 ± 10.2 [80.6 to 91]	89.1 ± 7.5 [85.3 to 92.9]	-0.19*	87.4 ± 7.5 [83.7 to 91.3]	90.0 ± 6.0 [86.9 to 93.0]	0.19*
L5L5	84.3 ± 8.4 [80.1 to 88.7]	86.9 ±6.7 [83.5 to 90.3]	0.17*	86.0 ± 7.0 [82.5 to 89.5]	87.7 ± 6.7 [84.3 to 91.1]	0.12*
L5S1	81.8 ± 6.4 [78.6 to 85.1]	81.7 ± 7.0 [78.1 to 85.2]	-0.01	81.3 ± 7.3 [77.6 to 85.0]	82.8 ± 7.9 [78.8 to 86.8]	-0.1

*Significant difference ($p \leq 0.05$) between baseline and week 16. *d* – Cohen's d

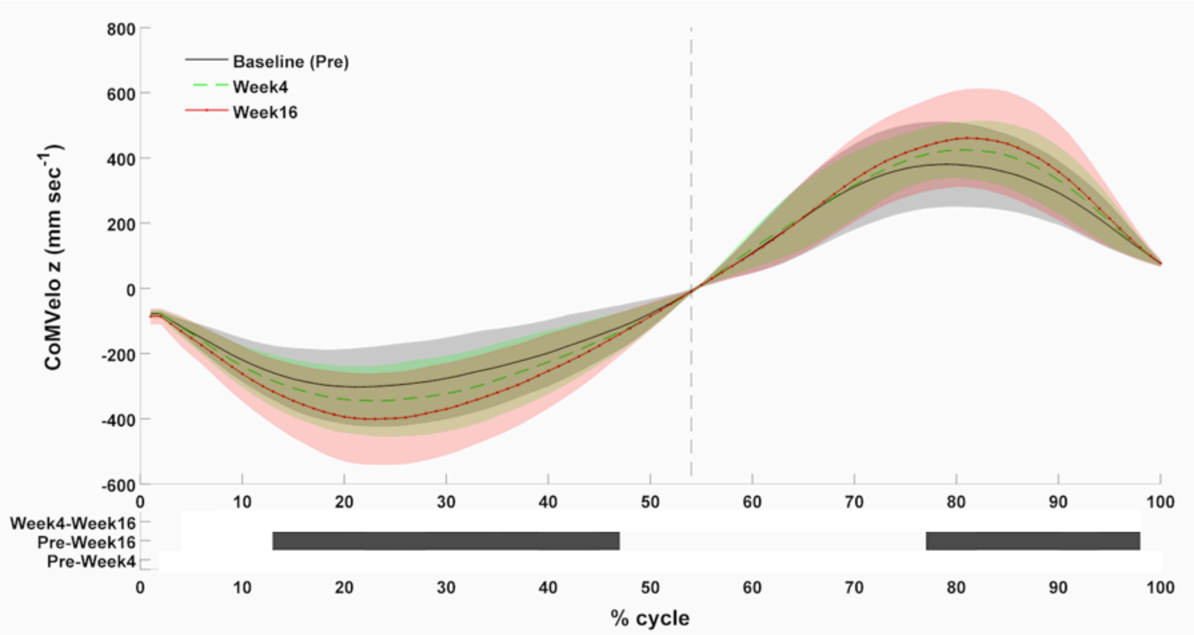

Figure 13: Waveform of the vertical centre of mass velocity (mm.sec-1) throughout the squat movement. Dark grey indicates areas of significant difference.

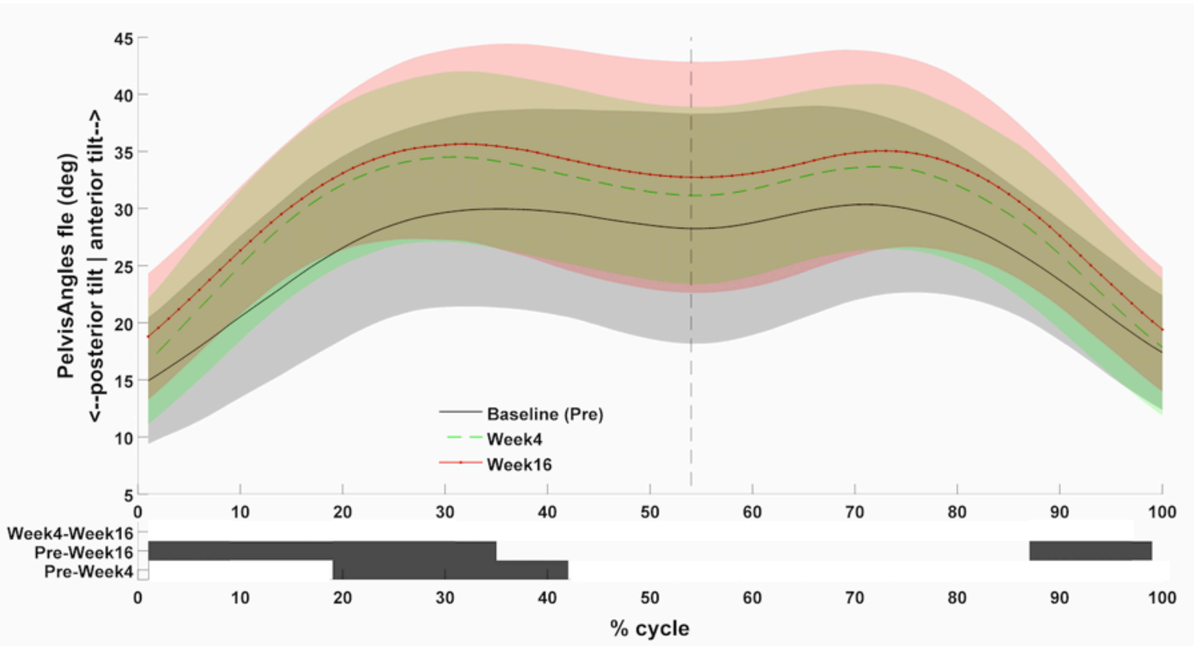

Figure 14: Waveform of the sagittal plane pelvis angles (degrees) throughout the squat movement. Dark grey indicates areas of significant difference.

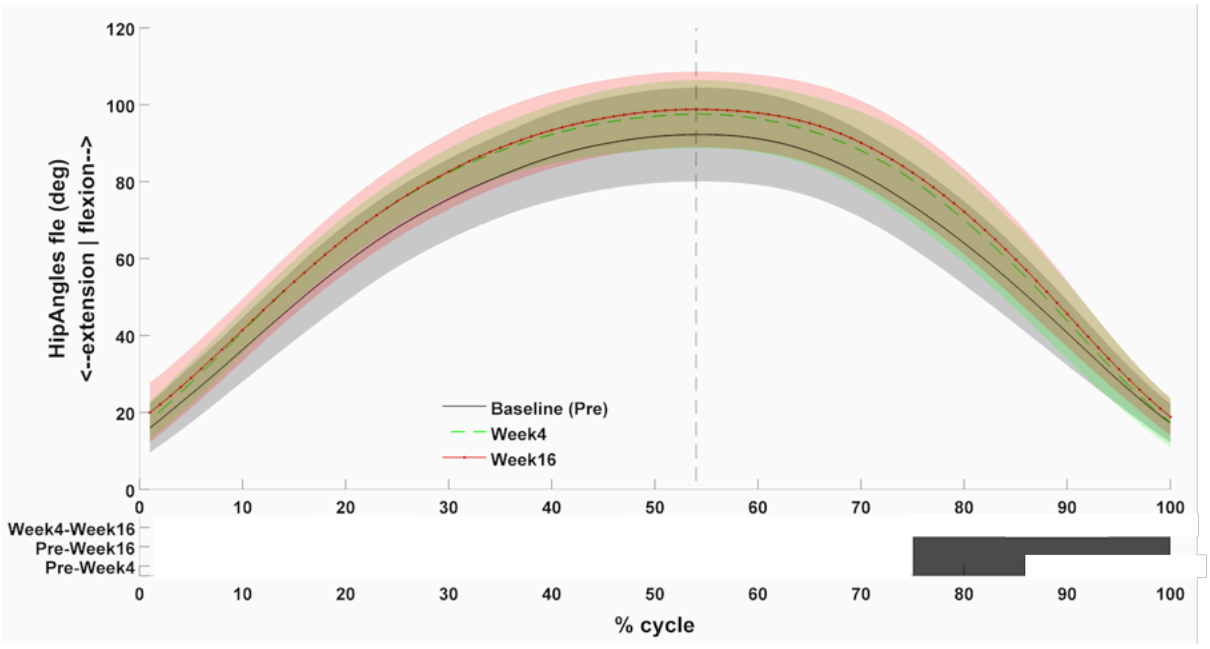

Figure 15: Waveform of the hip angles (degrees) throughout the squat movement. Dark grey indicates areas of significant difference.

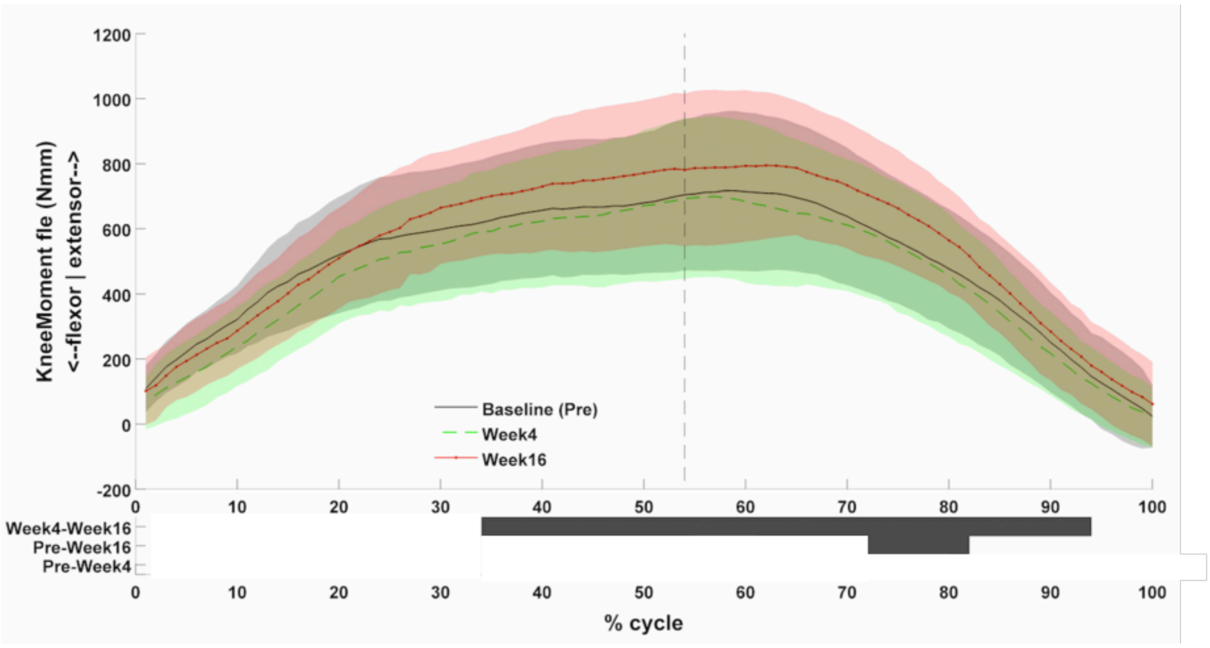

Figure 16: Waveform of the knee moment (Nmm) throughout the squat movement. Dark grey indicates areas of significant difference.

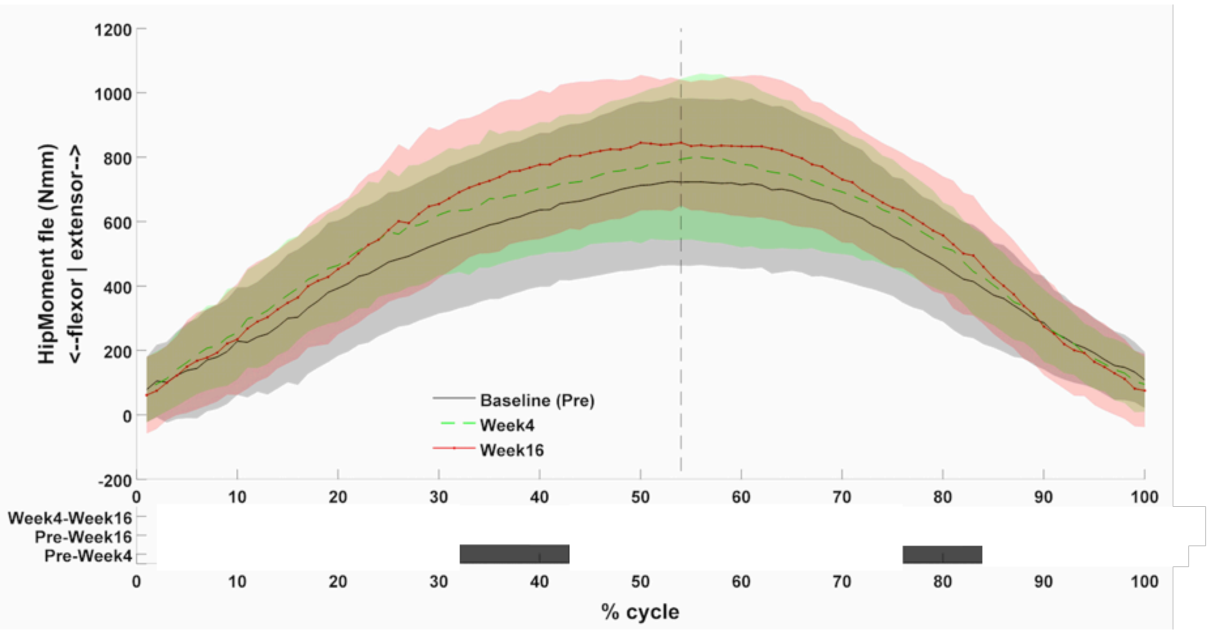

Figure 17: Waveform of the hip moment (Nmm) throughout the squat movement. Dark grey indicates areas of significant difference.

7.4 Discussion

The overall aim of the current study was to examine the effects of a free-weight based progressive resistance training intervention on pain, disability, quality of life, MRI-defined lumbar fat infiltration and functional cross-sectional area (FCSA), squat biomechanics and maximum strength and endurance in those with chronic low back pain. The hypothesis that a significant reduction in low back pain would be observed alongside a significant increase in maximum strength and endurance was, in part, supported. This study demonstrates significant reductions in pain and disability (72% and 76% respectively) in patients with comorbidities presenting with low back pain following a 16-week resistance training program. These changes are large compared to other whole-body resistance training interventions where positive impacts on mean pain scores (26% (Jackson, Shepherd and Kell, 2011), 39% (Kell and Asmundson, 2009)) and disability (46% (Jackson, Shepherd and Kell, 2011), 40% (Kell and Asmundson, 2009)) have been described. The presence of a lower baseline disability level of the participants in the present study (22.9 ± 1.2 (vs 43.1±3.3) (Jackson, Shepherd and Kell, 2011) and 40.4±2.4 (Kell and Asmundson, 2009)), but similar baseline pain level, was noted. While it could be suggested the greater the levels of modifiable disability present, the greater the opportunity for possible enhancements, the opposite was seen.

The reduction in fat infiltration and increased FCSA observed in the lumbar paraspinals are in line with changes found elsewhere as a result of resistance training (Danneels *et al.*, 2001; Taaffe *et al.*, 2009). These changes represent a conditioning of the lumbar paraspinals, a deconditioning of which have been associated with low back pain (Mengiardi *et al.*, 2006; Kjaer *et al.*, 2007; Pezolato *et al.*, 2012; Fortin and Macedo, 2013). These changes may have enhanced force generation capabilities in this area (Jones *et al.*, 2008) improving load tolerance and contributing to reduced pain as has previously been observed in resistance training interventions (Searle *et al.*, 2015). Changes in fat infiltration and FCSA were seen at the L3L4 and L4L5 levels but not at the L5S1 level. It was noted that percentages of fat infiltration were much higher at L5S1 than those above pre and post intervention. This may suggest that a higher fat content at L5S1 is a relatively normal state thus limiting the scope for improvement, that higher levels of fat infiltration are more resilient to change or that the level of loading may have been lower in this region. These possibilities require further investigation.

A significant improvement in endurance during the Biering-Sorensen test was observed in line with other studies (Kell and Asmundson, 2009). This is indicative of an increased ability to resist lumbar flexion which, when viewed with the changes in fat infiltration, suggests improved conditioning of the lumbar extensors, a deconditioning of which has been suggested as a risk factor for low back pain (Steele, Bruce-Low and Smith, 2014a). An interesting finding is that no significant increase in maximum strength or explosive strength measured using the isometric mid-thigh pull were seen despite participants observed to be lifting greater loads dynamically throughout the intervention. It is possible that the increases in loads lifted in the exercises were as a result of neural changes, common in resistance training (Aagaard, 2003; Gabriel, Kamen and Frost, 2006) specific to each exercise. Therefore, despite enhanced skill acquisition and greater loads lifted in each exercise throughout the intervention, peak force and rate of force development measured during the isometric mid-thigh pull were not enhanced. It is also possible that participants were fearful of lifting due to beliefs about their low back pain and unwilling to lift loads close to their true maximum in order to increase their maximum strength. This may mean that the increase in observed loads lifted throughout the intervention were due, in part, to increased confidence rather than increased maximum strength and explosive strength.

Increased velocity was observed throughout the squat movement mirroring the findings of Shum et al (Shum, Crosbie and Lee, 2005). They found significantly higher velocities in asymptomatic participants during sit to stand movements suggesting that slower movements were used to prevent provocation of pain. These muscle guarding patterns that utilise reduced speed have been listed as a movement impairment for those with low back pain (O'Sullivan, 2005). Associations have also been made between fear avoidance beliefs and low back pain (Nagarajan and Nair, 2010) and it has also been shown that those with low back pain demonstrate protective guarding behavior (Shum, Crosbie and Lee, 2007). This represents a freezing of degrees of freedom which is seen in early skill acquisition (Vereijken *et al.*, 1992) and is achieved by increasing tone in the surrounding musculature (Bernstein, 1967). The present intervention differed from comparable resistance training studies (Kell and Asmundson, 2009; Jackson, Shepherd and Kell, 2011) by addressing patient beliefs which has been suggested can increase patient activity levels (Swinkels-meewisse *et al.*, 2006) potentially breaking down belief based barriers to the RT. It utilised external cueing to enhance motor learning (Wulf, 2013) and free-weight exercises with higher intensity loading (75-83% RM vs 55-83% RM) to maximise the motor control challenge (Haff, 2000) and mechanical stimulus. Adaptations to this type of resistance training include altered agonist antagonist co-activation patterns (Gabriel, Kamen and Frost, 2006), or an un-freezing of degrees of freedom, and muscle hypertrophy (Schoenfeld, 2010). It is possible that the combined effect of these differences led to the larger improvements in pain and disability demonstrated within the current study. Regarding the increased hip flexion and pelvis tilt angles, these changes likely occurred as a result of the resistance training cueing aimed at reducing the lumbar flexion and active extension patterns that have been associated with low back pain (O'Sullivan, 2005). To the author's knowledge, this is the first study to demonstrate altered motor patterns in those with low back pain using free-weight resistance training. Moreover, these alterations moved participants towards the increased movement velocities seen in asymptomatic populations (Shum, Crosbie and Lee, 2005). Future work could utilise electromyography to observe changes in muscle recruitment patterns.

This intervention applies many of the concepts that would be commonplace in training sporting populations, including progressive overload and high intensity resistance training (Ratamess *et al.*, 2009) with the aim of changing the way the participant moves. This study demonstrates that it is possible to impact many of the factors that have been suggested to contribute to low back pain by applying basic resistance training practices.

Limitations

Two different MRI lumbar spine protocols were utilised as a number of participants had existing 1.5T MRI images at presentation. To prevent unnecessary repeat imaging, these were not duplicated. The 1.5 T imaging came without the pixel-spacing values necessary to compare FCSA between different images. The study was a cohort design, and whilst the inclusion of a comparison cohort would have added strength to the results, this was a pilot intervention and as such future work may be used to determine effectiveness relative to other interventions. Further, given the logistics involved in bringing participants into the clinic, oftentimes with them having to take time away from work, it was not possible to arrange a familiarisation session prior to the initial testing. It should therefore be noted that there is the possibility that a learning effect impacted the changes observed across the physical tests alongside the possibility that true maximum performance was not achieved within those tests.

7.5 Conclusions

This study demonstrated changes in lumbar fat infiltration and functional cross sectional area, lumbar muscle endurance and squat biomechanics throughout a 16-week free-weight resistance training intervention in participants with chronic low back pain. This is the first study to identify changes in fat infiltration as an objective marker of improvement and highlights that changes are can be observed across comorbidities. Positive outcomes including reduced pain and disability, improvement in quality of life, strength endurance and lumbar paraspinal muscle quality in patients with low back pain were seen, whereas changes in maximum strength were not observed.

8 A comparison of ground reaction force based variables during cutting, maximum strength, explosive strength, reactive strength and deceleration tasks in those with and without athletic groin pain

8.1 Introduction

Athletic groin pain is a chronic musculoskeletal condition that is common among both amateur and professional athletes participating in field sports (Waldén, Hägglund and Ekstrand, 2015). High rates of athletic groin pain have been observed in Gaelic Football (13.5/1000 hours) (Wilson *et al.*, 2007), in Rugby Union (2.5/1000 hours) (Brooks *et al.*, 2005) and Australian Rules Football (2.5/1000 hours) (Orchard and Seward, 2002). Given the pervasiveness of athletic groin pain and the explosive, high force movements involved in field sports, developing a full understanding of the neuromuscular factors including maximum strength, explosive strength, reactive strength and deceleration that contribute to the condition is required in order to develop effective treatment interventions and enhance performance on return to play.

Cutting is a common task in field sports with high numbers of cuts observed in elite soccer (Bloomfield, Polmam and O'Donoghue, 2007). However, despite the prevalence of athletic groin pain in field sports, only one study has yet investigated between-group (injured versus non-injured) differences in the biomechanics of cutting. Edwards et al (Edwards, Brooke and Cook, 2017) observed less knee flexion and hip internal rotation (ES = 0.61 to 0.94), and greater knee abduction and internal rotation, T12-L1 forward flexion, ipsilateral flexion and rotation and vertical ground reaction forces (ES = 0.67 to 1.17) in those with athletic groin pain compared to those with no history of athletic groin pain during a 45° cutting task. While this study increased understanding of the biomechanics associated with athletic groin pain during cutting, no horizontal ground reaction forces were reported. Given that horizontal force production has been associated with enhanced cutting performance (Havens and Sigward, 2015a), understanding whether horizontal force production alters in those with athletic groin pain could assist in the design of rehabilitation interventions. Further, the demands of cutting differ depending on the angle of the cut (Havens and Sigward, 2015c). No studies have yet investigated the difference in cutting performance and biomechanics between those with and without athletic groin pain in cuts of differing angles.

Levels of maximum strength about the hip have been associated with athletic groin pain. Results from three systematic reviews highlight that lower levels of hip adduction strength are consistently associated with athletic groin pain (Ryan, DeBurca and Mc Creesh, 2014; Whittaker *et al.*, 2015; Kloskowska *et al.*, 2016). Additionally, lower levels of hip abduction strength have been observed in those who develop athletic groin pain (O'Connor, 2004). In field sports where athletic groin pain is common, there is a requirement to use whole-body, closed chain actions to produce force. However, in the studies mentioned above, hip strength was only measured using single joint open chain assessments. To date, no studies have investigated whole-body closed chain strength in those with athletic groin pain. This may be important because injury may impact force production throughout the whole kinetic chain rather than solely about the hip (Castanharo *et al.*, 2011).

Deficits or reductions in explosive strength qualities have been observed in those rehabilitating across a broad range of injuries using isokinetic dynamometry. For example, explosive strength deficits have been observed in those rehabilitating from anterior cruciate ligament reconstruction surgery (Knezevic *et al.*, 2015; Blackburn *et al.*, 2016) in those with prior hamstring injury (Opar *et al.*, 2013) and in those with low back pain (Rossi *et al.*, 2017) when compared to non-injured populations. However, only one study to date has considered whole-body measures of explosive strength, finding no difference in counter-movement jump height between athletes with and without athletic groin pain (Moreno-Perez *et al.*, 2017). In addition, deficits in the ability to decelerate during landings have been observed in those rehabilitating from ACL injury (Pozzi *et al.*, 2017), from knee meniscal injury (Ford *et al.*, 2014) and in those with acute (C. Doherty *et al.*, 2014) and chronic (C Doherty *et al.*, 2014) ankle instability. Reactive strength is the ability of an individual to quickly move between an eccentric and concentric movement utilising the stretch shortening cycle and is commonly measured using the reactive strength index (RSI) (Young, 1995). It has been suggested as an important aspect of cutting (Spiteri *et al.*, 2017). The relationship between reactive strength and injury is poorly understood with only two studies found measuring RSI in those post-anterior cruciate ligament injury (Flanagan, Galvin and Harrison, 2008; Setuain *et al.*, 2015). No studies have yet considered reactive strength or deceleration in those with athletic groin pain. Work is needed to explore whether athletic groin pain impacts explosive strength, deceration and reactive strength

The above whole-body strength qualities have been given greater consideration in relation to cutting performance. Greater levels of maximum strength, explosive strength, reactive strength and deceleration have all demonstrated significant relationships (r = -0.75 to -0.38; ES = 0.94 to 1.88) with enhanced cutting performance (Swinton *et al.*, 2014; Delaney *et al.*, 2015; Spiteri *et al.*, 2015; Spiteri, Newton and Nimphius, 2015). This is relevant in athletic groin pain populations given the high prevalence in those participating in fields sports. Within such sports, where cutting is a common activity, faster cuts are deemed synonomous with enhanced performance (Spiteri *et al.*, 2017). Therefore to rehabilitate athletes to high levels of athletic performance, it is necessary to understand to what extent performance is impacted by injury. This has yet to be explored within an athletic groin pain population.

The main aim of this exploratory study is to examine if athletic groin pain affects performance by measuring ground reaction force based variables in cuts of different angles. The secondary aim is to examine if there are differences in maximum strength, explosive strength, deceleration and reactive strength measures in these same groups. This will be achieved by using principal component analysis and simulation testing to compare athletes with and without athletic groin pain as well as injured and non-injured limbs in those with athletic groin pain.

8.2 Methods

Fifty Gaelic football players (24.8 years ± 7.1 years; 179cm ± 5.5cm; 79.7kg ± 9.2kg) gave their consent to be participants in this cross-sectional exploratory study. All participants were amateur but consistently trained for their sport four to six times per week and had a resistance training history greater than two years. They were divided into two groups: the first consisting of 25 participants, from a squad of 32, with no athletic groin pain, the second consisting of 28 field sport athletes who were attending a large Sports Medicine Clinic to attempt rehabilitation from their condition. The athletic groin pain group all reported unilateral pain in the anterior hip and groin area while playing Gaelic football with symptom duration longer than 4 weeks. Participants were excluded if deemed to have hip joint arthrosis [grade 3 or higher on MRI (Li *et al.*, 1988)] or had an underlying medical condition such as inflammatory arthropathy or infection.

A ten-camera motion analysis system (Bonita B10, Vicon, UK), synchronised with two 40 x 60 cm force platforms (BP400600, AMTI, USA) was used to collect kinetic and kinematic data for cutting and tests of maximum strength, explosive strength, deceleration and reactive strength (45° and 110° cuts, isometric mid-thigh pull, single-leg squat jump, single-leg landing and single-leg drop jump respectively). The Vicon Plug-in-Gait marker set was used as per Marshall et al (Marshall *et al.*, 2014). Twenty-four reflective markers were placed on bony landmarks at the lower limb, pelvis and trunk. Simultaneous kinematic and kinetic data (200Hz, 2000Hz) were collected using a software package (Nexus 2, Vicon Motion Systems, UK). These data were filtered using a fourth-order low-pass Butterworth filter (cut-off frequency 15Hz)(Kristianslund, Krosshaug and Bogert, 2012). This data collection formed part of a larger study in which 3-dimensional kinematic data was also collected, but only the ground reaction force (GRF) data were analysed in the present study. All participants completed a standardised warm up consisting of two minutes jogging, five forward, backward and lateral lunges on each leg, 8 deep squats and five countermovement jumps. The order of which limb was tested first was randomised but remained consistent throughout all of the tests. The testing order was: a planned 110° cutting task, a planned 45° cutting task, single-leg drop jump, a single-leg drop landing, a single-leg squat jump and an isometric mid-thigh pull maximum strength test.

The 110° cut has been described previously (Marshall *et al.*, 2014) with timing gates added (Fusion Sport Smartspeed, Queensland, Australia) at two metres before and after the cutting point to measure cutting time (Figure 18A). The timing gates were set 1.5 metres apart from each other at a height of 1.2 metres. The 45° cut had the same timing gates set two metres before and two metres after the cutting point at an angle of 45° from the centre of the plates and the midline between the timing gates (Figure 18B). The distance of two metres was chosen as it allowed only one step prior to the cut to increase the emphasis on the acceleration component of the cut. It was thought that this would more closely represent explosive strength in cutting while the 110◦ cut would involve a greater deceleration component. Participants started 30cm behind the first timing gate in a staggered stance, and were instructed to complete the task as fast as possible. Participants were asked to repeat the task if they took a backwards step prior to moving forwards or if a full contact with the force plate wasn't achieved. The reason for allowing a longer overall approach to the 110° cut was to ensure a deceleration component to the movement keeping it in line with other decelerative cut tasks, such as the 505-test, in the literature. Reliability has previously been demonstrated to be fair to excellent within the Sports Surgery Clinic laboratory (ICC = 0.4 to 0.91) (Marshall *et al.*, 2014). These findings are in line with those observed elsewhere (ICC = 0.73 to 0.91) during similar cutting tasks (Mok, Bahr and Krosshaug, 2018).

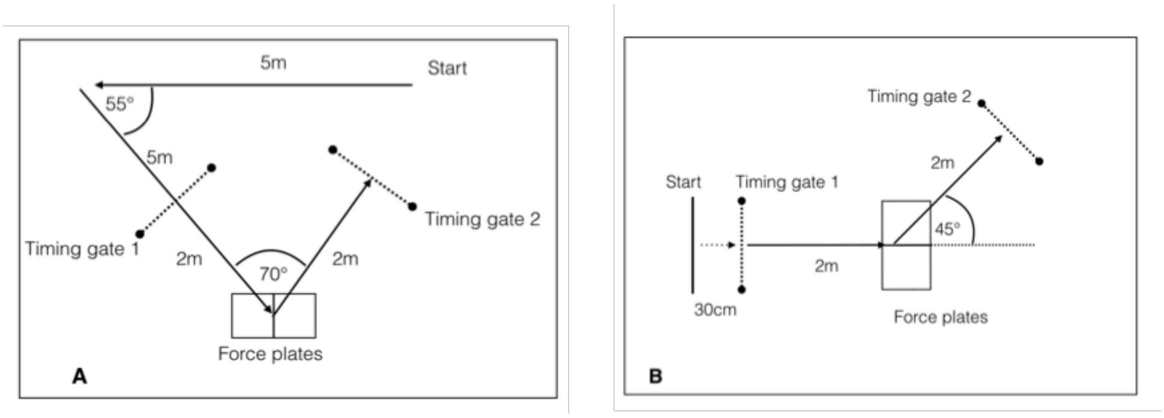

Figure 18: Layout for the A) 110° cut and B) the 45° cut

The single-leg drop jump was used to measure reactive strength on both legs and was performed from a box (height 20cm) set at 2cm away from the force plates. Participants stood on their jumping leg with their hands on their hips and their toes over the edge of the box and were instructed to drop off the box, onto one of the force plates and "jump as high as possible with as short a ground contact as possible, landing on two legs on the force plates". Trials were discounted and repeated if participants were adjudged to have jumped up from the box thereby increasing the drop height, if they removed their hands from their hips," or if they landed forward of the force plate from their jump. Reliability of this task has been measured within the Sports Surgery Clinic laboratory demonstrating good to excellent ICC (0.65 to 0.97).

The single-leg drop landing was used as a measure of deceleration and was tested on both legs. Participants stood on their test leg with their hands on their hips and their toes over the edge of a 30cm box placed in front of the force plates. They were instructed to "drop off the box onto the force plate landing on the same leg they were stood on and to absorb the landing as fast as possible and to hold the landing position for two seconds". Trials were discounted if participants were adjudged to have jumped up from the box thereby increasing the drop height, if they removed their hands from their hips, if the opposite leg touched the ground or if they were unable to hold the landing position for two seconds. Reliability of this measure has been previously demonstrated to be good to excellent (CMC = 0.80 to 0.99) (Myer, Bates and Foss, 2016).

The single-leg squat jump was used to measure explosive strength on both legs without the use of the stretch shortening cycle (Van Hooren and Zolotarjova, 2017). Participants stood on one force plate with their hands on their hips, standing on their jumping leg and adopting a self-determined quarter squat position. They were instructed to stand still in the quarter squat position for 2 seconds then jump as high as possible, in as short a time as possible, without using a countermovement. Trials were repeated if they took their hands off their hips or were adjudged (from the vertical ground reaction force trace) to have utilised a countermovement to initiate the jump. Reliability of this exercise has been previously demonstrated to be good to excellent (ICC = 0.88 to 0.91) (Kockum and Heijne, 2015).

The isometric mid-thigh pull is commonly used to measure maximum strength (Beckham *et al.*, 2013; Townsend *et al.*, 2017) and was used to this end in the current study. A customised set-up (Fittech, Australia) over the two force plates was employed as per a previous study from our laboratory (Welch *et al.*, 2015). The height of the bar was set as the mid-point between the anterior superior iliac spine and the top of the patella measured while the participant stood with a knee flexion angle of around 140° measured with a goniometer. Grip was enhanced with the use of weightlifting wrist wraps. Participants familiarised themselves and warmed up by completing a pull at approximately 50%, 75% and 90% of their maximum effort. They then completed 3 trials of a pull and were instructed keep their shoulders over the bar, look straight ahead and pull the bar up as fast and hard as they could for 3 seconds. Participants had 30 seconds rest between each trial. Reliability of this measure has previously been shown to be excellent (ICC 0.80 to 0.99) (Drake, Kennedy and Wallace, 2017).

Data analysis

Variables of interest for the 45° and 110° cuts can be seen in Table 29. Impulses and rates of force development over the first 25ms and 50ms of eccentric and concentric phases across all three planes, resultant of the horizontal planes and resultant of all three planes were calculated. The above timings (25ms and 50ms) were selected as the minimum length of time for an eccentric phase was 50ms. Ratios between the vertical and combined horizontal impulses were calculated for the whole ground contact as well as for the independent eccentric and concentric phases. The contact phase for the cuts began when the vertical ground reaction force first went above 20N and ended when it went below 20N. The eccentric phase was defined from the start of the cut to when the centre of mass power reached zero and the concentric phase being from that point until the end of the cut contact phase. Performance outcome in the cuts was defined as time from passing the first timing gate to the second.

Table 29: Variables of interest for the 45° cut and 110° cut

Variable	**Z**	**X**	**Y**	**XY**	**XYZ**
Eccentric RFD 25ms, 50ms	✓	✓	✓	✓	✓
Concentric RFD 25ms, 50ms	✓	✓	✓	✓	✓
Eccentric impulse 25ms, 50ms	✓	✓	✓	✓	✓
Concentric impulse 25ms, 50ms	✓	✓	✓	✓	✓
Eccentric impulse	✓	✓	✓	✓	✓

Eccentric impulse ratio	✓			✓	
Concentric impulse	✓	✓	✓	✓	✓
Concentric impulse ratio	✓			✓	
Peak force	✓	✓	✓		
Position of peak force	✓				
Completion time	N/A	N/A	N/A	N/A	N/A
Total ground contact time	N/A	N/A	N/A	N/A	N/A
Eccentric ground contact time	N/A	N/A	N/A	N/A	N/A
Concentric ground contact time	N/A	N/A	N/A	N/A	N/A

Z – vertical plane, X -lateral plane, Y -anterior plane, XY – resultant of horizontal planes, XYZ – resultant of all three planes

Variables of interest for the isometric mid-thigh pull (IMTP), single-leg squat jump, single-leg drop landing and the single-leg drop jump can be seen in Table 30. The reactive strength index was calculated by dividing jump height by contact time (Flanagan, Comyns and Rugby, 2008). Vertical stiffness was calculated as the ground reaction force at the end of the eccentric phase divided by the centre of mass displacement from the start of the movement to the end of the eccentric phase (Brughelli and Cronin, 2008; Gore *et al.*, 2018). Jump heights were calculated as the difference in vertical centre of mass height at toe off and the maximum vertical centre of mass height during the flight phase.

Table 30: Ground reaction force variables measured from tests of maximum strength, explosive strength, deceleration and reactive strength

Variable	**IMTP**	**SLDJ**	**SLSJ**	**SLDL**
Jump height		✓	✓	
Reactive strength index		✓		
Jump/deceleration/ground contact time		✓	✓	✓
Peak vertical force	✓	✓	✓	✓
Median vertical force	✓			
Pre-jump impulse			✓	
Position of peak force		✓	✓	✓

Vertical stiffness		✓		✓
Vertical RFD to peak force	✓	✓	✓	✓
Vertical RFD 25ms		✓	✓	✓
Vertical RFD 50ms	✓	✓	✓	✓
Horizontal RFD 25ms, 50ms		✓	✓	✓
Resultant RFD 25ms, 50ms		✓	✓	✓
Vertical RFD 100ms, 250ms, 500ms	✓			
Vertical impulse 25ms		✓	✓	✓
Vertical impulse 50ms	✓	✓	✓	✓
Horizontal impulse 25ms, 50ms		✓	✓	✓
Resultant impulse 25ms, 50ms		✓	✓	✓

IMTP – isometric mid-thigh pull, SLDJ – single-leg drop jump, SLSJ – single-leg squat jump, SLDL – single-leg drop landing, RFD – rate of force development

The single-leg drop jump was defined as the first and last points where vertical ground reaction force reached 20N. The start of the single-leg squat jump was defined as the last point prior to peak centre of mass power, where ground reaction force was at bodyweight. The end was defined as the final point at which the ground reaction force reached less than 20N. The start of the single-leg squat jump was defined as the final point prior to peak force where the force was equal to bodyweight and the end was defined as the final point at which the ground reaction force reached less than 20N. Although participants were instructed to utilise no countermovement, close visual inspection of the force-time curves revealed that often a small countermovement was used. To attempt to measure this, the next point prior to the start at which force was equal to bodyweight was identified. The area above the curve but below bodyweight was calculated as the pre-jump impulse. The start and end of the single-leg drop landing (the deceleration time) was defined as the point where the ground reaction force first reached greater than 20N to the point where the vertical centre of mass power first returned to zero. The start of isometric mid-thigh pull was defined as the first point where vertical ground reaction force reached 1.2 x bodyweight.

Statistical analysis

A challenge with exploratory biomechanical analyses is the interpretation of results given large number of variables available for analysis. To reduce the high number of variables, a data reduction technique, principal component analysis (PCA), was used to identify and examine patterns of variation in each of the performance tests across all participants. Before applying the PCA, discrete measures were centred (subtraction of mean) and normalised (divided by standard deviation) (Joliffe, 1986). To solely examine key variables of a pattern, all PCA loadings below 75% of the absolute maximum were zeroed. While this made principal components non-orthogonal, it simplified the interpretation and captures only the effects of features that affect the pattern of variation (Thorpe *et al.*, 2016). This is similar to the idea of analysis of characterising phases (Richter *et al.*, 2014) but used within features. Principle component scores were then determined by calculating the inner product between principal component and subject feature vector.

To measure the difference between injured and non-injured groups and between injured and non-injured limbs a simulation approach was taken. One trial of the exercise was selected at random from each participant. For the un-injured group, this was selected at random from either limb. For the injured group, the trial was selected at random from trials on the injured limb (no participants who completed the study reported pain on both sides). An independent samples T-test was performed to understand the size of the difference between groups. This process was repeated 100 times with the mean of the between-group differences used. Cohen's *d* was used to denote effect size. Thresholds used were 0.2, 0.6 and 1.2 for small, moderate and large between-group differences, respectively (Hopkins *et al.*, 2009). When the effect was in one direction for greater than or equal to 95% of the simulations used, the result was considered relevant. Data processing was carried out using MATLAB (R2015a, MathWorks, Natick, MA, USA).

8.3 Results

When considering the 45° cut, four principle components demonstrated between-group differences (Table 31). Injured athletes demonstrated a large effect for slower completion times (*d* = 1.39), a moderate effect for longer ground contact times (*d* = 0.73), a small effect for lower centre of mass power (*d* = -0.54) and a moderate effect for greater proportion of vertical to horizontal force production (*d* = -0.44). When considering between-limb differences in the athletic groin pain group (injured vs un-injured limbs) 45° cut (Table 33), a small effect for slower cuts were observed on the injured limb (*d* = 0.29).

Within the 110° cut five principal components demonstrated between-group differences, (Table 31). Injured athletes demonstrated a small effect for slower completion time (*d* = 0.41), a small effect for a longer eccentric ground contact time (*d* = -0.37), a small effect for greater peak force and early rate of force development (*d* = 0.31), a small effect for greater early concentric force in (*d* = 0.19) and a small effect for shorter ground contact times (*d* = -0.19). When considering between-limb differences in the athletic groin pain group (injured vs un-injured limbs) during the 110° cut (Table 33): peak force appears later in the injured limb (*d* = 0.35) and lower early vertical force and rate of force development were observed in the injured limb (*d* = -0.32).

In relation to deceleration ability, five principle components within the single-leg drop landing demonstrated between-group differences (Table 32). Injured athletes demonstrated a moderate effect for lower vertical force during the first 25ms (*d* = 1.03), a moderate effect for greater resultant of all three planes rate of force development during the first 50ms of the landing (*d* = 0.82), a moderate effect for greater horizontal resultant impulse over the first 25ms (*d* = 0.72), a longer landing time (*d* = -0.33) and lower vertical stiffness (*d* = -0.30). When considering between-limb differences in the athletic groin pain group (injured vs un-injured limbs) (Table 33), one principal component was identified, describing a small effect for greater early horizontal impulse in the injured limb (*d* = 0.50).

When considering reactive strength, six principal components within the single-leg drop jump demonstrated between-group differences (Table 32). Injured athletes demonstrated a moderate effect for lower jump height and reactive strength (*d* = 0.96), a moderate effect for greater early horizontal impulse (*d* = 0.62), a small effect for longer ground contact times (*d* = 0.44) with the final three principal components describing moderate effects for lower early horizontal rate of force development (*d* = -0.46, -0.40 and 0.30). When considering between-limb differences in the athletic groin pain group (injured vs un-injured limbs) (Table 33), two principal components demonstrated small effects, with greater early rate of force development in the injured limb (*d* = -0.28) and greater early horizontal force (*d* = 0.28) in the injured limb.

In relation to explosive strength, four principle components within the single-leg squat jump demonstrated between-group differences (Table 32). The injured group demonstrated a moderate effect for injured athletes demonstrating a lower jump height (*d* = -0.84), a moderate effect for lower early horizontal forces (*d* = -0.70), a moderate effect for greater pre-jump impulses (*d* = 0.61) and a small effect for lower early forces and rate of force development (*d* = -0.56). When considering between-limb differences in the athletic groin pain group (injured vs un-injured limbs) (Table 33), a small effect for lower jump height on the injured limb (*d* = 0.20) was evident.

When considering maximum strength, five principle components within the isometric mid-thigh pull demonstrated between-group differences (Table 32). Injured athletes demonstrated a small to moderate effect for lower rate of force development over 100ms (*d* = -1.05), 250ms (*d* = -0.95), 50ms (*d* = -0.88), 500ms (*d* = -0.54) and a small effect for a lower median vertical ground reaction force (-0.27). No principal components demonstrated between-limb differences in the athletic groin pain group (injured vs un-injured limbs) for the isometric mid-thigh pull.

Table 31: Identified principal components within the 45° and 110° cuts with between-group differences

Exercise	Principal component factors (factor loading)	Interpretation of principal components	*d*
45° cut	Completion time (-0.92)	Slower completion time in injured group	1.39
45° cut	Concentric ground contact time (0.52); total ground contact time (0.55)	Longer ground contact times in injured group	0.73
45° cut	Vertical centre of mass power (0.78)	Lower vertical power in injured group	-0.54
45° cut	Peak X force (0.36); peak XY force (0.36); total Z to XY impulse ratio (-0.45); concentric Z to XY impulse ratio (-0.42); eccentric Z to XY impulse ratio (-0.42)	Greater proportion of vertical to horizontal force production in injured group	-0.44
110° cut	Completion time (-0.93)	Slower completion time in injured group	0.41
110° cut	Eccentric GCT (-0.59); XYZ eccentric impulse (-0.46)	Longer eccentric ground contact time in injured group	-0.37
110° cut	Peak XY force (0.36); peak X force (-0.35); peak Z force (0.41); eccentric XY RFD over first 50ms (0.35); eccentric XYZ RFD over first 50ms (0.37); eccentric Z RFD over first 50ms (0.38)	Greater peak force and early RFD in injured group	0.31
110° cut	Concentric resultant horizontal impulse over first 25ms (0.38); 50ms (0.34); concentric total resultant impulse over first 25ms (0.43); 50ms	Greater early concentric force in injured group	0.19

	(0.40); concentric vertical impulse over first 25ms (0.45); 50ms(0.4137)		
110° cut	Concentric GCT (-0.50); total GCT (-0.51); eccentric AP impulse (-0.40)	Longer ground contact time in injured group	-0.19

GCT – ground contact time, AP – anterior posterior, RFD – rate of force development, X – lateral plane, XY – resultant horizontal plane, XYZ – total resultant plane, Z – vertical plane

Table 32: Identified principal components within the single-leg squat jump, single-leg drop jump and IMTP for between-group differences

Exercise	**PC factors (factor loading)**	**Interpretation of principal components**	***d***
SL drop landing	Vertical impulse over 25ms (-0.64); vertical RFD over first 25ms (-0.52)	Lower early vertical force production in injured group	1.03
SL drop landing	Resultant RFD of all three planes over first 50ms (0.91)	Greater resultant RFD in injured group	0.82
SL drop landing	Resultant horizontal impulse over first 25ms (0.86)	Greater early horizontal impulse in injured group	0.72
SL drop landing	Ground contact time (0.77)	Longer landing time in the injured group	-0.30
SL drop landing	Vertical stiffness (0.74)	Lower stiffness in injured group	-0.29
SL squat jump	Jump height (0.78)	Lower jump height in injured group	-0.84
SL squat jump	XY impulse over first 25ms (0.72); 50ms (0.63)	Lower early horizontal forces in injured group	-0.70

SL squat jump	Pre-jump impulse (0.98)	Greater impulse in injured group	0.61
SL squat jump	XYZ impulse over first 50ms (0.33); XYZ RFD over first 25ms (0.42); Z RFD over first 25ms (0.39); 50ms (0.42)	Lower early force and RFD in injured group	-0.56
SL drop jump	Jump height (-0.64); RSI (-0.64)	Lower height and reactive strength in injured group	0.96
SL drop jump	XY impulse over first 25ms (-0.85)	Greater early horizontal impulse in injured group	0.62
SL drop jump	Ground contact time (0.70)	Longer ground contact time in injured group	0.44
SL drop jump	XY RFD over first 25ms (-0.99)	Lower early horizontal RFD in injured group	-0.46
SL drop jump	XY RFD over first 50ms (-0.92)	Lower early horizontal RFD in injured group	-0.40
SL drop jump	XYZ RFD over first 25ms (-0.60); Z RFD over first 50ms (-0.58)	Lower early RFD in injured group	0.30
IMTP	Vertical RFD across first 100ms (1.0)	Lower RFD in injured group	-1.05
IMTP	Vertical RFD across first 250ms (1.0)	Lower RFD in injured group	-0.95
IMTP	Vertical RFD across first 50ms (1.0)	Lower RFD in injured group	-0.88
IMTP	Vertical RFD across first 500ms (-0.98)	Lower RFD in injured group	-0.54
IMTP	Median vertical GRF (0.81)	Lower GRF in injured group	-0.25

RFD - rate of force development, RSI - reactive strength index, d - Cohen's d, PC – principal component, XY – resultant horizontal plane, XYZ – resultant of all three planes, Z – vertical plane, GRF – ground reaction force, SL – single-leg, IMTP – isometric mid-thigh pull

Table 33: Injured versus non-injured limb differences in athletic groin pain group

Exercise	**Principal component factors (factor loading)**	**Interpretation of principal components**	***d***
45° cut	Completion time (-0.92)	Slower completion time on injured limb	0.29
110° cut	Position of peak vertical GRF (0.79)	Peak force appears later in injured group	0.35
110° cut	Concentric XYZ impulse over first 25ms (0.40); eccentric Z impulse over first 25ms (0.45); 50ms (0.36); eccentric XYZ RFD over first 25ms (0.40); eccentric Z RFD over first 25ms (0.45)	Lower vertical force and RFD in injured limb	-0.32
SLDL	XY impulse 25ms (0.86)	Greater early horizontal impulse in injured limb	0.50
SLSJ	Jump height (0.78)	Lower jump height in injured limb	-0.23
SLDJ	XYZ RFD over first 25ms (-0.60); Z RFD over first 50ms (-0.58)	Greater early RFD in injured limb	-0.28
SLDJ	XY impulse over first 25ms (-0.85)	Greater early horizontal force on injured limb	0.28

RFD – rate of force development, d – Cohen's d, XY – resultant horizontal plane, XYZ – resultant of all three planes, Z – vertical plane, GRF – ground reaction force

8.4 Discussion

The primary aim of the current study was to examine the differences in ground reaction force variables during 110° and 45° cuts between those with and without athletic groin pain. The hypothesis that slower cuts and lower levels of force would be observed in the injured athletes and in the injured limb was in part supported. Injured athletes demonstrated slower completion times, longer ground contact times, lower vertical power and a greater proportion of vertical to horizontal forces within the 45° cut. They also showed slower cuts on the injured compared to the non-injured limb. Similarly, within the 110° cut, injured athletes demonstrated slower completion times and longer ground contact times. Given that shorter ground contact times (Marshall *et al.*, 2014; Dos'Santos *et al.*, 2016) and greater horizontal impulses (Havens and Sigward, 2015a) have all demonstrated significant correlations with faster cut times, it is likely that the differences observed between the injured and non-injured groups within this study highlight differences in performance. It is possible that the reduced levels of performance are related to deconditioning due to reduced training (Neufer *et al.*, 1987) that is common with this injury (Holmich and Thorborg, 2014) and/or arthrogenic muscle inhibition which, while not directly observed in those with athletic groin pain, has been demonstrated chronic hip pain (Harris-Hayes *et al.*, 2014) and in unilateral hip musculature (Freeman, Mascia and Mcgill, 2013).

In contrast however, the remaining principle components within the 110° cut disagree with the hypothesis by highlighting higher early and peak forces and greater early concentric impulses in the injured group. Of interest is that a different relationship is present in the between-limb analysis which is in line with the hypothesis. The athletic groin pain group demonstrated peak force that occurred later during the ground contact and lower levels of force were produced during the first 25ms of ground the ground contact of the injured limb. This could be interpreted as a more tentative cutting step on the injured limb. These observations could suggest a combination between deconditioning that reduced an overall ability to dissipate force when compared to a non-injured population, but a greater attempt to do so on the injured limb. This is perhaps demonstrative of an altered strategy in an attempt to offload the painful area. It is also possible that the deceleration prior to the cut played a role. If attempting to reduce force through the injured side, there may have been a reduced deceleration with the injured limb prior to the cut on the non-injured limb resulting in a greater early impulse on the non-injured limb. The observed differences could also have caused the development of the condition in the first place; however a prospective study is required to appropriately explore this possibility.

The secondary aim of the study was to examine the differences in ground reaction force features in a series of maximum strength, deceleration, explosive strength and reactive strength tests in those with and without athletic groin pain and between injured and non-injured limbs in the athletic groin pain group. The hypothesis was in part supported that there would be deficits in maximum strength, explosive strength, deceleration ability and reactive strength in the injured group compared to the non-injured group and in the injured limbs compared to the non-injured limbs.

When considering deceleration, the injured group demonstrated lower early vertical forces, greater early horizontal forces, longer time to decelerate and lower levels of stiffness. The injured limb also demonstrated greater levels of horizontal force compared to the non-injured limb. These findings may represent an altered strategy in an attempt to reduce forces. Reductions in vertical ground reaction force (13%) have been observed during landings when athletes were coached to land softer (Elias, Hammill and Mizner, 2015). Athletes in the current study may have attempted to reduce force on landing to offload the injured site. This offloading strategy may have resulted in the greater levels of horizontal force production observed.

In relation to explosive strength, lower jump heights were observed in the injured group and also in the injured limb compared to the non-injured limb. Furthermore, lower early rate of force development, lower early horizontal impulses and greater attempt to use a counter movement strategy through a greater pre-jump impulse were observed in the injured group. Again, these differences may be indicative of unilateral reduction in conditioning in the injured limb. Given the differences observed at early time points and even in impulse prior to the jump it is possible that this is evidence of specific neural deconditioning. It has been observed that early rate of force development exhibits a stronger relationship with muscle pre-activation than maximum strength (de Ruiter *et al.*, 2004). It is possible that the reduction of impulse prior to the jump is representative of deconditioning of muscle pre-activation rather than alternative neural properties, for example, motor unit firing frequency which is more associated with maximum strength (Folland and Williams, 2007).

When considering reactive strength, lower reactive strength and height, longer ground contact times, greater early horizontal impulses and lower early force and rates of force development were observed in the injured group. This is the first study to investigate the differences in reactive strength between those with and without athletic groin pain. The current findings share some similarity with those of Gore et al (Gore *et al.*, 2018) who observed reduced levels joint and whole-body stiffness in those with athletic groin pain during a hurdle hopping task. They also suggested that observed differences are in response either to deconditioning or altered strategy to offload painful structures.

In relation to maximum strength, lower median force was observed in the isometric mid-thigh pull in the injured group suggesting a lower level of strength. Lower rate of force development from 50ms through to 500ms were also observed in the injured group. Rate of force development can be divided into early (≦ 100ms) and late phase (>100ms) (Andersen *et al.*, 2010) with early rate of force development demonstrating stronger relationship with early neural properties such as pre-activation and late rate of force development demonstrating a stronger relationship with maximum strength (Folland, Buckthorpe and Hannah, 2014). The findings in relation to the isometric mid-thigh pull highlight between-group differences in both early and late phase rate of force development as well as median force, suggesting detraining effects in both explosive strength and maximum strength. It is possible, given the isometric nature of the test and the relatively upright position, that the differences observed are less likely to be due to an offloading strategy. In this position of relative hip extension, it is observed from clinical experience to be less aggravating.

This is the first study to investigate the differences in whole-body maximum strength, explosive strength, reactive strength and deceleration abilities between those with and without athletic groin pain. Deficits were observed between group and between limb across all of these measures. Deficits have also consistently been observed in maximum strength and explosive strength in injured populations across a range of conditions in isometric or isokinetic tests (Angelozzi *et al.*, 2012; Opar *et al.*, 2013; Petersen *et al.*, 2014; Blackburn *et al.*, 2016) where there is limited opportunity to alter technique. It is therefore likely the observations in the current study are due, at least in part, to a broad deconditioning of neuromuscular capacity rather than just a consistent set of offloading strategies across all tests. This deconditioning would be due to reduced training volumes or arthrogenic muscle inhibition (Harris-Hayes *et al.*, 2014).

Training interventions should seek to restore neuromuscular qualities to ensure restoration of performance on return to play for those rehabilitating from athletic groin pain. Further, unilateral strategies should be considered to reduce between limb differences in neuromuscular qualities to ensure that there are no large differences in capacity to express and absorb force on return to play that could affect performance

Limitations

A limitation related to the current study is that, while between-group and between-limb differences were observed, it is not possible to determine if these were as a result of the injury or if they were present prior to the injury and were a contributing factor in the onset of the condition. Prospective work is required to determine this. Further, this was an exploratory analysis that examined between-group differences in cutting performance and neuromuscular strength qualities in a wide variety of variables. Future work should seek to build on this by using the results of the current study for hypothesis testing.

8.5 Conclusion

Deficits in cutting performance, maximum strength, explosive strength, reactive strength and deceleration were observed between groups. Similar deficits were also observed between limbs in the injured group. These differences are likely due to a combination of a deconditioning of neuromuscular qualities due to detraining and/or arthogenic muscle inhibition and efforts to offload injured or painful structures by utilising alternative strategies. Rehabilitation interventions should seek to restore neuromuscular qualities to enhance performance on return to play.

9 The effects of additional explosive strength training in the rehabilitation of athletes with athletic groin pain

9.1 Introduction

Athletic groin pain is a common injury in field sports that involve repetitive twisting, kicking and turning. In male soccer for example, athletic groin pain has been reported to account for 12–16% of all soccer injuries (Werner *et al.*, 2009). While three systematic reviews have identified wide variety of risk factors associated with athletic groin pain (Ryan, DeBurca and Mc Creesh, 2014; Whittaker *et al.*, 2015; Kloskowska *et al.*, 2016), common across all three reviews is a link between lower levels of strength and the greater occurrence of athletic groin pain.

Given the presence of athletic groin pain in field sports where cutting tasks are common, the role of cutting biomechanics has also been explored with respect to athletic groin pain. Edwards et al (Edwards, Brooke and Cook, 2017) observed less knee flexion and hip internal rotation (ES = 0.61 to 0.94), and greater knee abduction and internal rotation, T12-L1 lateral flexion and rotation, vertical force, and force in weight acceptance (ES = 0.67 to 1.17) in those with athletic groin pain compared to those with no history of athletic groin pain during a 45° cutting task. Given the presence of modifiable risk factors and differences observed in cutting biomechanics, further understanding of the effectiveness of interventions targeting changes in these factors is necessary to improve efficacy in rehabilitation from athletic groin pain.

In a systematic review, exercise therapy that includes strengthening exercises was found to be an effective means of rehabilitating athletic groin (Charlton *et al.*, 2017). It was suggested that exercise interventions that utilise external loading of the hip and strengthening of the abdominal musculature were the most effective. Given the relationship between cutting and athletic groin pain it is perhaps surprising that only one study (King *et al.*, 2018) has examined the effects of an exercise intervention on cutting biomechanics in those with athletic groin pain. The intervention included local hip and whole chain strengthening exercises along with linear running and cutting technique training, and resulted in medium to strong effect sizes for greater trunk control and increased ankle work (ES = 0.51 to 0.79) following the intervention. These changes were observed alongside concomitant improvements in symptoms (ES = 0.59 to 1.78) suggesting a potential relationship between the changes in cutting biomechanics and reduction in symptoms. However, while the intervention included the use of whole chain strengthening exercises, no measure of whole chain strength was taken and so it is unclear if changes in strength also played a role in the symptom changes observed.

Deficits in explosive strength and deceleration are commonly observed in those rehabilitating from injury (Ford *et al.*, 2014; Knezevic *et al.*, 2015; Opar *et al.*, 2015; Blackburn *et al.*, 2016; Pozzi *et al.*, 2017) and training interventions can lead to improved explosive strength in these populations (Kristensen and Burgess, 2013; Bieler *et al.*, 2014). However, no studies have yet investigated whether changes in explosive strength occur during rehabilitation from athletic groin pain and whether interventions that specifically target explosive strength lead to enhanced rehabilitation outcomes.

The first aim of this study is to examine if, for those with athletic groin pain, the inclusion of additional explosive strength training in their rehabilitation intervention results in changes in ground reaction force based variables in difference tasks (cutting, maximum strength, explosive strength, reactive strength and deceleration). The second aim is to examine the effects of additional explosive strength training on outcome measures and return to play time.

9.2 Methods

The initial design of this study was to undertake an RCT. A power analysis using the an effect size of 0.5 (mean effect of the biomechanical variables reported in the study by king et al (King *et al.*, 2018)), an alpha level of 0.05 and a power of 0.8 revealed 51 participants in each group. However, once the study was underway, it became apparent from both the rate of recruitment and the dropout rates that the desired number of participants would not be obtained within a suitable timeframe. The decision was made to perform a pre-post analysis of those who completed rehabilitation to understand the changes pre- to post-intervention. A final number of twenty-nine participants (24.9 ± 7.9 years; 80kg ± 7.3; 181cm ± 4.8) with athletic groin pain were recruited for the study. All participants were experienced multidirectional field sport athletes and were attending a large Sports Medicine Clinic to attempt rehabilitation from their condition. They all reported pain in the anterior hip and groin area while playing Gaelic football with symptom duration longer than 4 weeks. Participants were excluded if deemed to have hip joint arthrosis [grade 3 or higher on MRI (Li *et al.*, 1988)], could not complete the rehabilitation program due to time or equipment constraints, did not intend on returning to pre-injury activity levels or if they had an underlying medical condition such as inflammatory arthropathy or infection. Due to the original study design, participants were randomly assigned to one of two groups. Group one (n = 15), the no-jump group, acted as control and consisted of rehabilitation with one of two physiotherapists experienced in the rehabilitation of athletic groin pain. The rehabilitation has been outlined previously (King *et al.*, 2018) and can be found in Appendix 2: Athletic groin pain rehabilitation intervention. The jump intervention group (n = 14) received the same rehabilitation, with one of the same two physiotherapists as the no-jump intervention group, with the additional inclusion of explosive strength training. This additional training was the inclusion of three sets of five double leg squat jumps loaded with a 20kg bar and 3 sets of five bodyweight only single-leg squat jumps on each leg. These were alternated across each level 1 training session and were completed as the first multi-segmental exercise within the session. Each repetition of the squat jumps were instructed to be maximal effort. Level 1 training sessions continued throughout the whole length of the rehabilitation.

Of the twenty-nine participants that entered the study, ten did not return for follow up assessment. Two of these were within the jump group and the remaining eight from the no-jump group. This is similar to dropout rates observed elsewhere (King *et al.*, 2018). The reasons given by participants were: travel distance for return to the clinic for review (n = 3), other commitments (n = 2) and other injury (n = 1) with the remaining being non-contactable for reason of non-return (n = 4).

A 10-camera motion analysis system (Bonita B10, Vicon, UK), synchronised with two 40 x 60 cm force platforms (BP400600, AMTI, USA) was used to collect kinematic and kinetic (sampled at 200Hz and 2000Hz respectively) data for all tests. The Vicon Plug-in-Gait marker set was used as per Marshall et al (Marshall *et al.*, 2014). Twenty-four reflective markers were placed on bony landmarks at the lower limb, pelvis and trunk. These data were filtered using a fourth-order low-pass Butterworth filter (cut-off frequency 15Hz) (Kristianslund, Krosshaug and Bogert, 2012). This data collection formed part of a larger study in which 3-dimensional kinematic data was also collected, but only the ground reaction force (GRF) data were analysed in the present study. Participants completed the HAGOS questionnaire at the beginning of each biomechanical assessment to measure symptoms. This measure has demonstrated excellent reliability (ICC 0.82 to 0.91) (Thorborg *et al.*, 2011). All participants completed a standardised warm up consisting of two minutes jogging, five forward, backward and lateral lunges on each leg, 8 deep squats and five countermovement jumps. The order of which limb was tested first was randomised but remained consistent throughout all of the tests. The testing order was; planned 110° cutting task, a planned 45° cutting task, single-leg drop jump, a single-leg drop landing, a single-leg squat jump and an isometric mid-thigh pull maximum strength test.

The 110° change of direction task has been described (Marshall *et al.*, 2014) with the addition of timing gates (Fusion Sport Smartspeed, Queensland, Australia) at two metres before and after the force plates. The timing gates were set 1.5 metres apart at a height of 1.2 metres (Figure 19A). The 45° change of direction had the same timing gates set 2 metres before the force plates and two metres on the far side at an angle of 45° from the centre of the plates and the midline between the timing gates (Figure 19B). Participants started 30cm behind the first timing gate in a staggered stance. The 2 metre distance before the plate was selected as it for only one foot-contact prior to the change of direction limiting the technical aspect of organising the lower body prior to change of direction. Participants were instructed to complete the task as fast as possible and were asked to repeat the task if they took a step backwards prior to moving forwards and if a full contact with the force plate wasn't achieved. Reliability has previously been demonstrated to be fair to excellent within the Sports Surgery Clinic laboratory (ICC = 0.4 to

0.91) (Marshall *et al.*, 2014). These findings are in line with those observed elsewhere (ICC = 0.73 to 0.91) during similar cutting tasks (Mok, Bahr and Krosshaug, 2018).

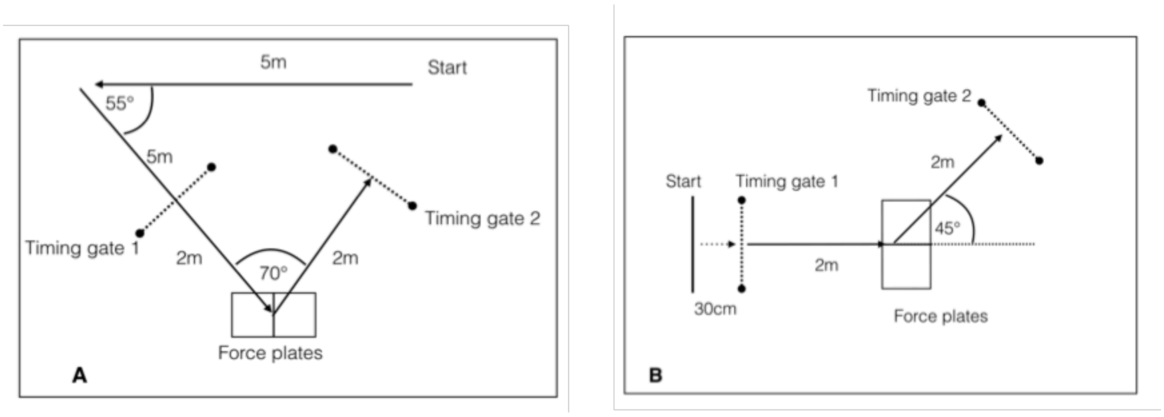

Figure 19: Layout for the A) 110° cut and B) the 45° cut

The single-leg drop jump was used to measure reactive strength and was performed from a box (height 20cm) set at 2cm away from the force plates. Participants stood on their jumping leg with their hands on their hips and their toes over the edge of the box and were instructed to drop off the box, onto one of the force plates and "jump as high as possible with as short a ground contact as possible, landing on two legs on the force plates". Trials were discounted and repeated if participants were adjudged to have jumped up from the box thereby increasing the drop height, if they removed their hands from their hips," or if they landed forward of the force plate from their jump. Reliability of this task has been measured within the Sports Surgery Clinic laboratory demonstrating good to excellent ICC (0.65 to 0.97).

During the single-leg drop landing, participants stood on their test leg with their hands on their hips and their toes over the edge of a 30cm box placed in front of the force plates. They were instructed to drop off the box onto the force plate landing on the same leg they were stood on and to absorb the landing as fast as possible and to hold the landing position for two seconds". Trials were discounted if participants were adjudged to have jumped up from the box thereby increasing the drop height, if they removed their hands from their hips, if the opposite leg touched the ground or if they were unable to hold the landing position for two seconds. Reliability of this measure has been previously demonstrated to be good to excellent (CMC = 0.80 to 0.99) (Myer, Bates and Foss, 2016).

The single-leg squat jump was used to measure explosive strength without the use of the stretch shortening cycle (Van Hooren and Zolotarjova, 2017). Participants stood on one force plate with their hands on their hips, standing on their jumping leg and adopting a self-determined quarter squat position. They were instructed to stand still in the quarter squat position for 2 seconds then jump as high as possible, in as short a time as possible, without using a countermovement. Trials were repeated if they took their hands off their hips or were adjudged (from the vertical ground reaction force trace) to have utilised a countermovement to initiate the jump. Reliability of this exercise has been previously demonstrated to be good to excellent (ICC = 0.88 to 0.91) (Kockum and Heijne, 2015).

The isometric mid-thigh pull is commonly used to measure maximum strength (Beckham *et al.*, 2013; Townsend *et al.*, 2017) and was used to this end in the current study. A customised set-up (Fittech, Australia) over the two force plates was employed as per a previous study from our laboratory (Welch *et al.*, 2015). The height of the bar was set as the mid-point between the anterior superior iliac spine and the top of the patella measured while the participant stood with a knee flexion angle of around 140° measured with a goniometer. Grip was enhanced with the use of weightlifting wrist wraps. Participants familiarised themselves and warmed up by completing a pull at approximately 50%, 75% and 90% of their maximum effort. They then completed 3 trials of a pull and were instructed keep their shoulders over the bar, look straight ahead and pull the bar up as fast and hard as they could for 3 seconds. Participants had 30 seconds rest between each trial. Participants had 30 seconds rest between each trial. Reliability of this measure has previously been shown to be excellent (ICC 0.80 to 0.99) (Drake, Kennedy and Wallace, 2017).

Intervention

The intervention has been described elsewhere (King *et al.*, 2018) (Appendix 2: Athletic groin pain rehabilitation intervention) and consisted of three levels. The first addressed intersegmental strength and control, the second addressed linear running mechanics and gradual increase of running loads and level three addressed multidirectional mechanics and the transition back to sprinting (Figure 20: Components of rehabilitation and key performance indicators for progression).

Figure 20: Components of rehabilitation and key performance indicators for progression

The rehabilitation intervention is reported in detail in accordance with the template for intervention description and replication checklist and guide (Hoffmann *et al.*, 2014). The exercise selection was dictated by the technical ability of the participant.

Progression through the rehabilitation levels was based on the achievement of key performance indicators. Progression from level 1 to level 2 was indicated once the subject had a negative crossover sign (Thorborg, Bandholm and Hölmich, 2013) which was usually achieved by the second session. Progression from level 2 to level 3 was indicated once the subject had symmetrical internal hip rotation at 90°, pain-free squeeze at 45° and symptom free completion of the Linear A running program. Progression from level 3 to return to play and repeat 3D testing was symptom free completion of the Linear B running program and symptom free completion of the multidirectional drills at maximum intensity. At this point participants were cleared to return to full participation in their chosen sports.

Data analysis

Variables of interest for the 45° and 110° cuts can be seen in Table 34. Impulses and rates of force development over the first 25ms and 50ms of eccentric and concentric phases across all three planes, resultant of the horizontal planes and resultant of all three planes were calculated. The above timings were selected as the minimum length of time for an eccentric phase was 50ms. Ratios between the vertical and combined horizontal impulses were calculated for the whole ground contact as well as for the independent eccentric and concentric phases. The contact phase for the cuts began when the vertical ground reaction force first went above 20N and ended when it went below 20N. The eccentric phase was defined from the start of the cut to when the centre of mass power reached zero and the concentric phase being from then until the end of the cut contact phase. Performance outcome in the cuts was defined as time from passing the first timing gate to the second.

Table 34: Variables of interest for the 45° cut and 110° cut

Variable	**Z**	**X**	**Y**	**XY**	**XYZ**
Eccentric RFD 25ms, 50ms	✓	✓	✓	✓	✓
Concentric RFD 25ms, 50ms	✓	✓	✓	✓	✓
Eccentric impulse 25ms, 50ms	✓	✓	✓	✓	✓
Concentric impulse 25ms, 50ms	✓	✓	✓	✓	✓
Eccentric impulse	✓	✓	✓	✓	✓
Eccentric impulse ratio	✓			✓	
Concentric impulse	✓	✓	✓	✓	✓
Concentric impulse ratio	✓			✓	
Peak force	✓	✓	✓		
Position of peak force	✓				
Completion time	N/A	N/A	N/A	N/A	N/A
Total ground contact time	N/A	N/A	N/A	N/A	N/A
Eccentric ground contact time	N/A	N/A	N/A	N/A	N/A
Concentric ground contact time	N/A	N/A	N/A	N/A	N/A

Z – vertical plane, X -lateral plane, Y -anterior plane, XY – resultant of horizontal planes, XYZ – resultant of all three planes

Variables of interest for the isometric mid-thigh pull (IMTP), single-leg squat jump, single-leg drop landing and the single-leg drop jump can be seen in Table 35. The reactive strength index was calculated by dividing jump height by contact time (Flanagan, Comyns and Rugby, 2008). Vertical stiffness was calculated as the ground reaction force at the end of the eccentric phase divided by the centre of mass displacement from the start of the movement to the end of the eccentric phase (Gore *et al.*, 2018). Jump heights were calculated as the difference in vertical centre of mass height at toe off and the maximum vertical centre of mass height.

Table 35: Table of variables that were calculated for each test of maximum strength, explosive strength, reactive strength and deceleration

Variable	**IMTP**	**SLDJ**	**SLSJ**	**SLDL**
Jump height		✓	✓	
Reactive strength index		✓		
Jump/deceleration/ground contact time		✓	✓	✓
Peak vertical force	✓	✓	✓	✓
Median vertical force	✓			
Pre-jump impulse			✓	
Position of peak force		✓	✓	✓
Vertical stiffness		✓		✓
Vertical RFD to peak force	✓	✓	✓	✓
Vertical RFD 25ms		✓	✓	✓
Vertical RFD 50ms	✓	✓	✓	✓
Vertical RFD 100ms, 250ms, 500ms	✓			
Horizontal RFD 25ms, 50ms		✓	✓	✓
Resultant RFD 25ms, 50ms		✓	✓	✓

SL – Single-leg, IMTP – Isometric Mid-Thigh Pull, RFD - Rate of Force Development, V - Vertical, CoM - Centre of Mass, RSI - Reactive Strength Index

The single-leg drop jump was defined as the first and last points where vertical ground reaction force reached 20N. The start of the single-leg squat jump was defined as the last point prior to peak centre of mass power, where ground reaction force was at bodyweight. The end was defined as the last time ground reaction force reached less than 20N. The start and end of the single-leg drop landing (the deceleration time) was defined as the point where the ground reaction force first reached greater than 20N to the point where the vertical centre of mass power first returned to zero. The start of isometric mid-thigh pull was defined as the first point where vertical ground reaction force reached 1.2 x bodyweight.

Statistical analysis

To measure between-group differences in descriptive statistics, pooled HAGOS scores and return to play times, an independent samples T-test was performed. A between group difference was considered 'clinically' relevant if an effect size of greater than or equal to 0.4 was observed. To measure the effect of the intervention on HAGOS between the two groups a two-way mixed ANOVA (group by time) was used. The HAGOS has demonstrated good to excellent reliability (ICC = 0.82 to 0.91) (Thorborg *et al.*, 2011).

A challenge with exploratory biomechanical analyses is the interpretation of results given large number of variables available for analysis. To reduce the high number of variables, a data reduction technique, principal component analysis (PCA), was used to identify and examine patterns of variation in each of the performance tests across all participants. Before applying the PCA, discrete measures were centred (subtraction of mean) and normalised (divided by standard deviation) (Joliffe, 1986). To solely examine key variables of a pattern, all PCA loadings below 75% of the absolute maximum were zeroed. While this made principal components non-orthogonal, it simplified the interpretation and captures only the effects of features that affect the pattern of variation (Thorpe *et al.*, 2016). This is similar to the idea of analysis of characterising phases (Richter *et al.*, 2014) but used within features. Principle component scores were then determined by calculating the inner product between principal component and subject feature vector.

To examine how the change in the biomechanical measures were affected by the two intervention groups and how the pooled group altered from pre- to post-intervention, a simulation approach was taken. One trial of the exercise from the injured limb pre- and post-intervention was selected at random for each participant in each group. The difference between pre- and post-measures was calculated. To account for differences in measures at baseline, pre-post changes for both groups were regressed together against pre-measures (in a point-by-point manner) and the residuals of the regression were calculated, as has been performed similarly elsewhere (Pataky, Vanrenterghem and Robinson, 2015). The difference between mean of the residuals between-groups was then calculated to give an adjusted between-group change. This process was repeated 100 times and the mean of the between group differences calculated. Variables were reported as 'clinically' relevant if they maintained the same direction of difference between groups for greater than or equal to 95% of the simulations. The same process was repeated for each of the tested exercises. Thresholds used were 0.2, 0.6 and 1.2 for small, moderate and large between group differences respectively (Hopkins *et al.*, 2009). This approach was taken for the differences between groups prior to the start of the intervention, at testing on return to play and in the changes throughout the intervention.

9.3 Results

The results of the descriptive analysis can be found in Table 36. Trivial to small effects were observed for the jump intervention group to be younger (*d* = -0.4), taller (*d* = 0.58), heavier (*d* = 0.04) and to return to play faster (*d* = -0.39). When measuring the difference in effects between -groups adjusted for baseline levels, two principal components were identified within the 45° cut (Table 37). The jump intervention group demonstrated moderate effects for a greater reduction in ground contact time (*d* = -0.73) and a greater increase in concentric impulse (*d* = 0.65) following the intervention. Two principal components were identified within the 110° cut (Table 37). The jump intervention group demonstrated moderate effects for a greater increase in peak vertical centre of mass power (*d* = 0.77) and a greater reduction in ground contact time (*d* = -0.73). One principal component was identified within the single-leg squat jump (Table 37). A small effect for a lower increase in horizontal impulse in the jump intervention group was observed (*d* = -0.55). One principal component was observed in the single-leg drop landing (Table 37). The jump group demonstrated a moderate effect for a greater increase in rate of force development over the first 50ms (*d* = 0.86).

When considering the pooled data, five principal components within the 110° cut (Table 38) demonstrated small to large effects for shorter ground contact time (*d* = -0.80), greater early concentric impulses (*d* = -0.55), faster completion times (*d* = 0.54), a greater horizontal to vertical impulse ratio (*d* = -0.51) and and earlier position of peak vertical force (*d* = -0.37) post-intervention. Four principal components within the 45° cut (Table 38) demonstrated small effects for shorter ground contact times (*d* = 0.46), faster completion times (*d* = 0.42), greater early eccentric forces (*d* = 0.30) and greater peak vertical forces (*d* = 0.29) post-intervention.

When considering the tests of neuromuscular strength qualities, a number of small effects for changes post-intervention were observed (Table 39). A greater rate of force development was observed in the single-leg squat jump (*d* = 0.53) and within the isometric mid-thigh pull (*d* = -0.40). Within the single-leg drop jump greater early rate of force development (*d* = -0.56), greater peak vertical forces (*d* = -0.46) and greater early impulses (*d* = -0.41) were observed. Within the single-leg drop landing, lower stiffness (*d* = 0.42) and shorter landing times (*d* = 0.41) were observed.

Analysis of the HAGOS subsections revealed no interaction effect between group and time for change in scores in any of the HAGOS subsections (Table 40: Hip and groin outcome scores pre- and post-intervention with results from the analysis of variance). Significant time effects (pre- versus post-intervention) were evident for: symptoms ($F(1,17) = 10.3$, p = 0.005), activities of daily living ($F(1,17) = 36.8$, p < 0.000), sport and recreation ($F(1,17) = 34.0$, p < 0.000), physical activity ($F(1,17) = 24.8$, p < 0.000) and quality of life ($F(1,17) = 105.7$, p < 0.000). Analysis of the HAGOS subsections for the pooled data revealed significant positive change in symptoms (*d* = -0.96), pain (*d* = -0.88), activities of daily living (*d* = -0.96), sport and recreation (*d* = -1.6), physical activity (*d* = -0.98) and quality of life (*d* = -0.92) (Table 41).

Table 36: Between-group differences in descriptive statistics and return to play times

	Jumps group mean ± st dev	**No jumps group mean ± st dev**	***d***
Age (years)	23.7 ± 7.4	27.4 ± 6.1	-0.4
Height (cm)	182 ± 3.9	179 ± 5.6	0.58
Weight (kg)	80.1 ± 8.4	79.8 ± 6.3	0.04
RTP (weeks)	12.9 ± 6.6	15.1 ± 6.7	-0.4

St dev - standard deviation, d - Cohen's d, RTP – return to play

Table 37: Principal components across all exercises that demonstrated greater between-group differences from pre- to post-intervention

Exercise	**Principal component variables (factor loading)**	**Interpretation**	***d***
45° cut	Concentric GCT (0.52) + total GCT (0.55)	Greater reduction in GCT in jump group	-0.73
45° cut	Conc XYZ impulse over first 25ms (0.43) and 50ms (0.41); concentric Z impulse over first 25ms (0.45 and 50ms (0.45)	Greater increase in concentric impulse in jump group	0.65
110°	Z centre of mass power (0.90)	Greater increase in concentric impulse in jump group	0.65
110°	AP eccentric impulse (0.40); concentric GCT (0.50); total GCT (0.51)	Greater increase in Z centre of mass power in jump group	0.77
SLSJ	XY impulse over first 25ms (0.72) and 50ms (0.64)	Greater increase in horizontal impulse in no-jump group	-0.55
SLDL	XYZ RFD over first 50ms (0.91)	Greater increase in RFD in jump group	0.86

XYZ – resultant of three planes, XY – resultant horizontal plane, Z – vertical plane, SLSJ – single-leg squat jump, SLDL – single-leg drop landing, GCT – ground contact time, RFD – rate of force development, AP – anterior posterior

Table 38: Principal components within the 110° and 45° cuts that demonstrate from pre- to post-intervention when all participants were pooled

Exercise	**Principal component variables (factor loading)**	**Interpretation**	***d***
110° cut	AP eccentric impulse (-0.40) + concentric GCT (-0.50) + total GCT (-0.51)	Shorter ground contact time	-0.80
110° cut	XY C Imp over first 25ms (0.38) + 50ms (0.34) + XYZ C Imp over first 25ms (0.43) + 50ms (0.40) + Z CImp over first 25ms (0.45) + 50ms (0.41)	Greater early concentric impulses	-0.55
110° cut	Completion time (0.95)	Faster completion time	0.54
110° cut	Ratio_of_Z_to_XY Imp total GC (-0.57) + C (-0.58) + E (-0.48)	Greater horizontal impulse component	-0.51
110° cut	Position of peak Z GRF (-0.79)	Earlier position of peak vertical force	-0.37
45° cut	C_GCT (0.49) + total GCT (0.54) + XYZ E Imp (0.4)	Shorter ground contact time	0.46
45° cut	Completion time (-0.94)	Shorter completion time	0.42
45° cut	XY Imp over first 25ms (-0.66) + XY RFD over first 25ms (-0.54)	Greater early eccentric force	0.30
45° cut	Peak Z force (-0.73)	Greater peak Z force	0.29

XYZ – resultant of three planes, XY – resultant horizontal plane, Z – vertical plane, GRF – ground reaction force, GCT – ground contact time, AP – anterior posterior, E – eccentric, C – concentric, Imp - impulse

Table 39: Principal components within tests of maximum strength, explosive strength, reactive strength and deceleration that demonstrate changes from pre- to post-intervention when all participants were pooled

Exercise	**Principal component variables (factor loading)**	**Interpretation**	**Cohen's *d***
SLSJ	Z RFD over first 150ms (-0.85)	Greater RFD	0.53
SLDJ	Z RFD over first 50ms(-0.75)	Greater RFD over first 50ms	-0.56
SLDJ	Peak_Z GRF (-0.93)	Greater peak vertical force	-0.46
SLDJ	Z impulse over first 25ms (0.76)	Greater impulse	-0.41
SLDL	Vertical stiffness (0.74)	Lower stiffness	0.42
SLDL	Total GCT (0.77)	Shorter landing time	0.41
IMTP	Z RFD over first 100ms (0.99)	Greater RFD	-0.40

XYZ – resultant of three planes, RFD – rate of force development, XY – resultant horizontal plane, Z – vertical plane, GRF - ground reaction force, GCT – ground contact time, SLSJ – single-leg squat jump, SLDJ – single-leg drop jump, SLDL – single-leg drop landing

Table 40: Hip and groin outcome scores pre- and post-intervention with results from the analysis of variance

HAGOS	Group	Pre-intervention (mean ± st dev)	Post-intervention (mean ± st dev)	Statistics
Symptoms	**No-jump**	62.2 ± 17.2	75.5 ± 12.6	Group: $F(1,17) = 0.81$, p = 38 Time*: $F(1,17) = 10.3$, $p = 0.005$ Int: $F(1,17) = 0.03$, $p = 0.86$
	Jump	67.3 ± 12.6	79.2 ± 11.1	
Pain	**No-jump**	85.0 ± 7.2	91.4 ± 7.0	Group: $F(1,17) = 0.14$, $p = 0.71$ Time: $F(1,17) = 0.37$, $p = 0.55$ Int: $F(1,17) = 0.07$, $p = 0.79$
	Jump	83.1 ± 10.8	90.6 ± 6.8	
ADL	**No-jump**	83.6 ± 9.9	92.1 ± 7.6	Group: $F(1,17) = 0.00$, $p = 0.99$ Time*: $F(1,17) = 36.8$, $p < 0.000$ Int: $F(1,17) = 0.38$, $p = 0.54$
	Jump	81.3 ± 17.9	93.3 ± 7.5	
Sport/rec	**No-jump**	55.4 ± 20.6	76.8 ± 16.5	Group: $F(1,17) = 0.18$, $p = 0.68$ Time*: $F(1,17) = 34.0$, $p < 0.000$ Int: $F(1,17) = 0.53$, $p = 0.48$
	Jump	52.9 ± 22.2	83.3 ± 10.1	
PA	**No-jump**	16.1 ± 21.3	28.6 ± 25.7	Group: $F(1,17) = 0.31$, $p = 0.59$ Time*: $F(1,17) = 24.8$, $p < 0.000$ Int: $F(1,17) = 1.89$, $p = 0.19$
	Jump	12.5 ± 19.2	45.8 ± 35.5	
QOL	**No-jump**	40.7 ± 17.2	57.9 ± 9.9	Group: $F(1,17) = 0.37$, $p = 0.55$ Time*: $F(1,17) = 105.7$, $p < 0.000$ Int: $F(1,17) = 0.01$, $p = 0.93$
	Jump	36.7 ± 14.3	55.0 ± 29.9	

*St dev - standard deviation, HAGOS - hip and groin outcome score, ADL – activities of daily living, rec – recreation, PA – physical activity, QOL – quality of life. * denotes a significant effect*

Table 41: Hip and groin outcome scores pre- and post-intervention with results from the T-test and effect size calculation

HAGOS	Pre-intervention (mean ± st dev)	Post-intervention (mean ± st dev)	*d*
Symptoms	65.4 ± 14.2	77.8 ± 11.5	-0.96*
Pain	83.8 ± 9.5	90.9 ± 6.7	-0.88*
ADL	82.1 ± 15.1	92.9 ± 7.3	-0.96*
Sport/rec	53.8 ± 21.1	80.9 ± 12.8	-1.6*
PA	13.8 ± 19.5	39.5 ± 32.6	-0.98*
QOL	38.2 ± 14.8	56.1 ± 24.1	-0.92*

** Denotes significant difference from pre- to post-interventionADL – activites of daily living, QOL – quality of life, rec - recreation HAGOS – hip and groin outcome score, st dev – standard deviation, d – Cohen's d*

9.4 Discussion

The initial aim at the outset of this study was to examine the effects of additional explosive strength training (in the form of additional weighted jumps) within a previously published athletic groin pain intervention on ground reaction force-based variables in cutting, maximum strength, explosive strength, reactive
Due to issues with the recruitment of participants these aims changed although both pooled and between-group analyses were performed. The results highlight improvements in cutting performance and measures of explosive strength and deceleration in reponse to the intervention across the whole group.

Shorter ground contact times and faster completion times were observed in both the 110° and 45° cuts from pre- to post-intervention in the pooled analysis. This is the first study to demonstrate improvements in cutting performance throughout rehabilitation in those with athletic groin pain. These performance improvements may have occurred for a number of reasons. One component of the rehabilitation intervention was cutting training with which improvements in cutting performance have been observed elsewhere (Lennemann *et al.*, 2013; Born *et al.*, 2016). Another factor that may have contributed to improved performance was an improvement in symptoms. Pain has been shown to result in altered neuromuscular force production (Rice *et al.*, 2015) with altered biomechanics also observed following injury (Trulsson *et al.*, 2015). It is possible that, as symptoms improved, neuromuscular function and biomechanical function simply changed in the absence or reduction of pain. However, differences in cutting biomechanics have been observed between those with and without a history of athletic groin pain on return to play (Edwards, Brooke and Cook, 2017). The reasons for the changes in biomechanics were not explored within the current study, therefore the cause of the biomechanical changes cannot be explained with certainty.

When considering the between-group analysis, a greater reduction in ground contact times was observed in the jump intervention group in both the 45° and 110° cuts. Furthermore, the jump intervention group demonstrated a greater increase in concentric impulses in the 45° cut and a greater increase in vertical centre of mass power in the 110° cut. While shorter ground contact times have consistently shown significant correlations with faster cuts (Sasaki *et al.*, 2011; Marshall *et al.*, 2014; Dos'Santos *et al.*, 2016), no between-group improvements in cutting time were observed. This therefore represents an alternative strategy for completion of the cutting tasks. This is possibly due, in part, to increased neuromuscular capacity and improved coordination in response to the intervention. Squat jumps were chosen for the intervention to place emphasis on concentric force production by reducing utilisation of the stretch-shortening cycle (Van Hooren and Zolotarjova, 2017). It appears that, given the increase in concentric impulse and vertical power observed in the jump intervention group, some specificity of transfer to the cut took place.

When considering explosive strength, within the single-leg squat jump a greater increase in horizontal impulse was observed in the no-jump group. This finding is in direct contrast to the hypothesis that greater increases in explosive strength would be observed in the jump intervention group. The standard intervention contained multi-directional training and linear running drills that could be considered reactive strength exercises. It has been observed elsewhere that reactive strength interventions can improve measures of explosive strength (Chelly *et al.*, 2010; García-Pinillos *et al.*, 2014). It therefore is possible that the volume of exposure to the squat jump training, particularly given the shorter return to play time observed in the jump intervention group, did not provide a large enough difference in stimulus to demonstrate a greater improvement in the jump intervention group as hypothesised. Another explanation is the presence of a ceiling effect due to the principle of diminishing returns (Peterson, Rhea and Alvar, 2005). It was observed that the jump intervention group, prior to the start of the intervention, demonstrated greater early impulses and rate of force development in all planes. While it was anticipated that the additional explosive strength training would elicit a greater increase in explosive strength variables, it is possible that, given the difference at the start of the intervention, the jump intervention was not able to stimulate further increases as they had reached a 'performance ceiling'. This principle of diminished returns effect has been observed elsewhere in response to training interventions (Rhea *et al.*, 2002; Gorostiaga *et al.*, 2004).

When considering deceleration, within the single-leg drop landing test, a greater increase in rate of force development over the first 50ms was observed in the jump intervention group. This differs from the no-jump group where a reduction in rate of force development (although not apparent in over 95% of the simulations) was observed. When considered alongside impulse variables and changes observed over the first 25ms, this appears to represent a difference in strategy. The jump intervention group demonstrated an increase in both impulse and rate of force development across both the first 25ms and 50ms of ground contact. The no-jump intervention group also demonstrated increases in impulse across 25ms and 50ms and rate of force development across 25ms. However, they demonstrated a reduction in rate of force development over the first 50ms of ground contact. The change in the no-jump group is achieved with a steeper rise in force over the first 25ms followed by a shallower increase in the next 25ms. The change in the jump group is achieved with upward movement of the whole force-time curve. The between-group differences observed may be as a result of the greater number of landings during the jump intervention. It is possible that the increase in eccentric rate of force development across both time-points in the jump intervention group contributed to the reduction in ground contact times observed during the cutting tasks. These findings are in agreement with findings elsewhere where reduced ground contact times during cutting have been observed in response to eccentric training (de Hoyo *et al.*, 2016). It would therefore appear that eccentric actions are important in performance during cutting and may have also contributed to the reduced rehabilitation times observed within the jump intervention group. This could be due to an improved ability to dissipate force during decelerations reducing load through the hip and groin.

No between-group differences in change in maximum strength (as measured by the isometric mid-thigh pull(or reactive strength (as measured by the single-leg drop jump) were observed. This is explained by the fact that the jump intervention group did not include any additional maximum strength or reactive strength training. Both groups did, however, demonstrate comparable increases in rate of force development measures in the isometric mid-thigh pull and in the single-leg drop jump. These changes highlight that the standard intervention provides an adequate stimulus to develop explosive and reactive strength qualities.

The second aim of the current study was to examine the effects of additional explosive strength training on outcome measures and return to play time. The hypothesis was in part supported in that there was a shorter return to play time in the jump intervention group. It is likely that an earlier improvement in explosive strength due to the extra volume of training contributed to the faster return to play times observed. On return to play there were no between-group differences in outcome measure based on the HAGOS questionnaire. These improvements are in line with previous research using the same standard intervention (King *et al.*, 2018). The jump intervention therefore had no greater effect on symptoms, pain, activities of daily living, sport and recreation, physical activity or quality of life on return to play. This was likely observed as all participants had already returned to play and so all had reached a reduced level of pain and symptoms, and increased function. However, the jump intervention group reached this level of symptoms in a shorter period of time.

It should be noted that an improvement in explosive strength in both groups together with a concomitant improvement in HAGOS on return to play was observed. It is likely that an improvement in conditioning of these explosive strength qualities therefore contributed to the improvement in HAGOS observed in both groups and in the pooled participants. This is supported by the results of the previous chapter (Table 32: Identified principal components within the single-leg squat jump, single-leg drop jump and IMTP for between-group differences) that demonstrate deficits in explosive strength and reactive strength in those with athletic groin pain compared to a non-injured group. The participants in the current study demonstrated increases in many of the variables where deficits, compared to the non-injured group, were observed.

Limitations

One limitation to this study is related to the difference in interventions within the pooled group analysis. If treated as a pilot analysis, the overall changes observed across the pooled group demonstrate interesting changes that are worthy of a follow-up study. Further, within the between-group analysis, due to the low numbers the chances of a type II error occurring are increased. One other limitation relates to the exposure to training. Given the criteria based progression throughout the rehabilitation program (p360), it is possible for athletes, depending on their symptom resolution, to be exposed to greater or lower volumes of level 2 and level 3 exercises. These are the levels that contain exercises that could be considered explosive strength and reactive strength exercises in the form of linear running and multidirectional drills. Future work should consider more frequent testing of explosive strength and reactive strength throughout the rehabilitation process to further determine the effects of these phases of rehabilitation on return to play times, HAGOS and on cutting performance. A further limitation is related to the definition of return to play. The definition in the current study, set as the return to full training, differs from some elsewhere. For example, Weir et al (Weir *et al.*, 2011) in their RCT measured return to play time as the number of weeks from treatment commencement to when the athlete returned to full activity at the same level. This can lead to issues of interpretation when comparing return to play times. If return to full activity at the same level is interpreted as starting in matches, this may lead to longer rehabilitation times as it could take longer for an athlete to play their way back into contention for a starting place. As such, care should be taken when comparing return to play times across interventions.

9.5 Conclusion

Improvements in maximum strength, explosive strength, reactive strength, deceleration and cutting biomechanics were observed in those rehabilitating from athletic groin pain. These changes occurred either in response to the training stimulus from the intervention or due to restoration of these qualities following reduced levels of pain. Further work is required to understand the impact of these strength qualities on rehabilitation from athletic groin pain. While it appears that specific differences related to the jump intervention occurred, further work with greater numbers of participants is required to understand the true impact of such targeted interventions.

10 Principal component analysis of the associations between kinetic variables in cutting and jumping, and cutting performance outcome

10.1 Introduction

The ability to change direction (cut) while sprinting is important for sports performance across a range of field sports (Sheppard and Young, 2006) that can occur in high volumes with 727 ± 203 cuts observed in soccer matches (Bloomfield, Polmam and O'Donoghue, 2007). Additionally, in respect of performance, it is an important ability because it is used to evade or respond to an opponent. Young et al. (Young, James and Montgomery, 2002) suggested that cutting performance is dependent upon three neuromuscular force production characteristics: maximum strength, explosive strength and reactive strength. These are necessary due to the various eccentric and concentric force demands observed during cutting (Brughelli *et al.*, 2008) and utilisation of the stretch shortening cycle highlighted by the relationship between higher levels of reactive strength and enhanced cutting performance (Delaney *et al.*, 2015).

Attempts have been made to understand the ground reaction force factors that relate to performance outcome in cutting, defined as a faster cut, across a variety of cutting angles. To date, those relationships between ground reaction force variables and performance outcomes have been mixed, with some investigations highlighting vertical and some highlighting horizontal variables as being important for performance. Dos'Santos et al. (Dos'Santos *et al.*, 2016) found significantly greater peak horizontal force (ES = 2.24) and lower vertical impact forces (ES = -1.19) in faster compared to slower athletes in a 180° cut. Spiteri et al. (Spiteri *et al.*, 2015) found greater braking and propulsive vertical peak force (ES = 1.88 to 2.31) and impulses (ES = 0.51 to 0.91) in faster performers of 180°, 90° and 45° cuts. Havens and Sigward (Havens and Sigward, 2015a) found no significant correlations between 45° cut performance outcome and horizontal ground reaction force variables, although total lateral impulse did significantly correlate (r = 0.53) with performance outcome in a 90° cut. Maloney et al (Maloney *et al.*, 2016) observed that summed ground reaction force symmetry (r = 0.47) significantly correlated with performance during a double 90° cutting task, but no significant correlations were observed between cutting performance and direction specific ground reaction forces. A possible reason for the range of variables could be the analyses performed. Spiteri et al. (Spiteri *et al.*, 2015) only considered vertical ground reaction force whereas the other studies considered both vertical and horizontal variables which would lead to different conclusions. Given the change in horizontal direction in cutting, it would seem important to analyse ground reaction forces in all three planes. Also, in all these studies, the ground reaction force variables were considered across the whole ground contact or across phases defined by kinematic or kinetic discrete points. For example, braking and propulsive phases have been defined by peak knee flexion or troughs in ground reaction force-time curves (Havens and Sigward, 2015a; Spiteri *et al.*, 2015; Dos'Santos *et al.*, 2016). Given shorter total ground contact time has consistently correlated with performance in cutting (Sasaki *et al.*, 2011; Marshall *et al.*, 2014; Havens and Sigward, 2015a; Spiteri *et al.*, 2015; Dos'Santos *et al.*, 2016; Maloney *et al.*, 2016) indicating the time in which force is produced is important for performance, it is perhaps surprising that no attempt has yet been made to understand the link between ground reaction forces during different phases defined by time, as opposed to being defined by kinematic or kinetic discrete points. Such an approach could provide strength and conditioning coaches with information that would inform training programme design.

One of the issues with biomechanical analyses is that it is possible to generate large numbers of variables which enhances the likelihood of a type I alpha error occurring when examining correlations. Principal component analysis (PCA) is a method of analysing a selection of discrete points that allows variables to be grouped by patterns of common variation that can be used to analyse the relationship with performance outcome. Principal component analyses have been used to analyse performance outcome in cutting tasks (Sporiš *et al.*, 2010; Salaj and Markovic, 2011) highlighting some commonality in performance outcome across different angled cuts. This suggests some transferability in skill in different cutting tasks but more work is needed to understand what ground reaction force variables are common across cuts of different angles that relate to enhanced cutting performance. To date, no study has utilised a principal component to understand how ground reaction forces determine cutting performance outcome across different angled cuts.

It is common for practitioners to utilise performance testing to gather information about selected abilities (e.g. maximum strength, explosive strength and reactive strength) of an athlete to improve performance by building a specific profile of the relative strengths and weaknesses of the athlete; this information can ultimately help coaches to develop an optimal neuromuscular training programme. Studies have observed significant correlations between maximum strength (r = -0.31 to -0.88; ES = 0.68) (Jones, Bampouras and Marrin, 2009; Nimphius, McGuigan and Newton, 2010; Spiteri *et al.*, 2015; Young, 2015), explosive strength (r = -0.34 to -0.65) (Barnes *et al.*, 2007; Delaney *et al.*, 2015) and reactive strength (r = -0.44; ES = 1.63) (Delaney *et al.*, 2015; Young, 2015) and cutting performance outcome. These studies give insight into the relationship that exists between outcome measures from selected abilities and cutting performance. However, no study has yet utilised a principal component analysis to investigate the relationship between maximum strength, explosive strength and reactive strength outcome and kinetic (impulse and rate of force development) measures with cutting performance outcomes.

The primary aim of this study is to determine the ground reaction force features in cutting related to performance outcome in different angled cuts. The secondary aim is to understand the relationship between ground reaction force features in a series of maximum strength, explosive strength and reactive strength tests and cutting performance outcome. It is hypothesised that variables associated with rapid ground reaction force production during different angles of cut are related to performance outcome. A second hypothesis is that rapid ground reaction force production qualities determined during tests of maximum strength, explosive strength and reactive strength also correlate with cutting performance outcome.

10.2 Methods

Twenty-five intercounty (23.5 ± 4.2years, 183 ± 6cm, 83 ± 6.9kg) male gaelic footballers from a squad of 32 accepted the invitation to participate in the study. Testing was approved by the Sports Surgery Clinic Ethics board (ref: 0017) and all participants provided informed consent prior to undertaking testing. Participants undertook a standardised warm up consisting of two minutes jogging, five forward, backward and lateral lunges on each leg, 8 deep squats and five countermovement jumps. All tests were carried out on both limbs with the order of which limb was tested first being randomised but remaining consistent for a participant across all tests in the testing session. Two cutting tasks were assessed: a 45° (Figure 1A), and a 110° cut (Figure 1B); along with 4 neuromuscular assessment tests: a single-leg drop jump, a single-leg drop landing, a single-leg squat jump and an isometric mid-thigh pull. Testing order was fixed (planned 110° cut, the planned 45° cuts, single-leg drop jumps, single-leg drop landings, single-leg squat jumps and the isometric mid-thigh pulls) to adhere to recommended ordering of performance tests (Harman, 2008). Participants were allowed two practice attempts prior to three trials at each task on each leg with 30seconds rest between repetitions. A ten-camera motion analysis system (Bonita B10, Vicon, UK), synchronised with two 40 x 60 cm force platforms (BP400600, AMTI, USA) was used to collect kinetic and kinematic data for all tests. Data was sampled at 200Hz and the Vicon Plug-in-Gait marker set was used as per Marshall et al (Marshall *et al.*, 2014). Twenty-four reflective markers were placed on bony landmarks at the lower limb, pelvis and trunk. Simultaneous kinematic and kinetic data (200Hz, 2000Hz) were collected using a software package (Nexus 2, Vicon Motion Systems, UK). These data were filtered using a fourth-order low-pass Butterworth filter (cut-off frequency 15Hz)(Kristianslund, Krosshaug and Bogert, 2012). This data collection formed part of a larger study in which 3-dimensional kinematic data was also collected, but only the ground reaction force (GRF) data were analysed in the present study.

The 110° cut (Figure 19A) has been described previously (Marshall *et al.*, 2014) with the addition of timing gates (Fusion Sport Smartspeed, Queensland, Australia) at two metres before and after the cutting point to measure cutting time. The timing gates were set 1.5 metres apart at a height of 1.2 metres. The 45° cut (Figure 19B) had the same timing gates set two metres before and two metres after the cutting point at an angle of 45° from the centre of the plates and the midline between the timing gates. The distance of two metres was chosen as it allowed only one step prior to the cut to increase the accelerative component and reduce the influence of deceleration the cut. Participants started 30cm behind the first timing gate in a staggered stance. Participants were instructed to complete the task as fast as possible. Participants were asked to repeat the task if they took a backwards step prior to moving forwards or if a full contact with the force plate wasn't achieved. The reason for allowing a longer overall approach to the 110° cut was to ensure a deceleration component to the movement keeping it in line with other decelerative cut tasks, such as the 505-test, in the literature. Reliability has previously been demonstrated to be fair to excellent (ICC = 0.4 to 0.91) within the sports surgery clinic biomechanics laboratory (Marshall *et al.*, 2014).

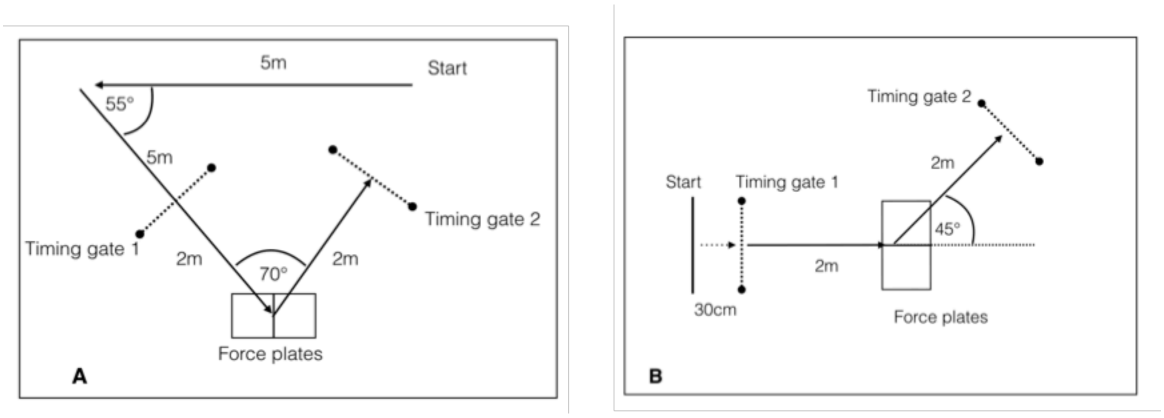

Figure 21: Layout for the A) 110° cut and B) the 45° cut

The single-leg drop jump (SL-drop jump) was used to measure reactive strength and was performed from a height of 20cm. Participants started on the jumping leg with their hands on their hips and their toes over the edge of the box and were instructed to drop off the box, which was placed 2cm from the edge of the force plates, onto the force plate jumping as high as they could with as short a ground contact as possible landing on two legs. Trials were discounted and repeated if participants were adjudged to have jumped up from the box thereby increasing the drop height, if they removed their hands from their hips or if they landed forward of the force plate from their jump. Reliability of this task has been measured within the Sports Surgery Clinic laboratory demonstrating good to excellent ICC (0.65 to 0.97).

As a method of measuring deceleration, a single-leg drop landing (SL-drop landing) was used. Participants stood on their test leg with their hands on their hips and their toes over the edge of a 30cm box placed 2cm in front of the force plates. A greater height of box than used for the single-leg drop jump was selected to accentuate the deceleration challenge. They were instructed to drop off the box onto the force plate landing on the same leg they were stood on and to absorb the landing as fast possible holding it for two seconds. Trials were discarded if participants were adjudged to have jumped up from the box thereby increasing the drop height, if they removed their hands from their hips, if the opposite leg touched the ground or if they were unable to hold the landing position for two seconds. Reliability of this measure has been previously demonstrated to be good to excellent (CMC = 0.80 to 0.99) (Myer, Bates and Foss, 2016).

The single-leg squat jump was used as a second measure of explosive strength and involved the athlete placing their hands on their hips, standing on their jumping leg and adopting a self-determined quarter squat position. They were instructed to jump as high as possible, in as short a time as possible, without using a countermovement. Trials were repeated if they took their hands off their hips or were adjudged (from the vertical ground reaction force trace) to have utilised a countermovement to initiate the jump. Reliability of this measure has been previously demonstrated to be good to excellent (ICC = 0.88 to 0.91) (Kockum and Heijne, 2015)

To measure maximum strength an isometric mid-thigh pull (IMTP) test was used. The set up for the test involved the use of a customised set up over the laboratory force plates (Fittech, Australia) (Welch *et al.*, 2015). Bar height was set by measuring the mid-point between the top of the patella and the anterior superior iliac spine and the distance from that point while standing up straight to the ground. Grip was enhanced with the used of weightlifting wrist wraps. Participants familiarised themselves by completing a pull at approximately 50%, 75% and 90% of their maximum effort. They then completed 3 trials of a pull and were instructed keep their shoulders over the bar, look straight ahead and pull the bar up as fast and hard as they could for 3 seconds. Participants had 30 seconds rest between each trial and had no sight of the force trace during the movement. Reliability of this measure has previously been shown to be excellent (ICC 0.80 to 0.99) (Drake, Kennedy and Wallace, 2017).

Data analysis

Variables of interest for all the maximum strength, explosive strength and reactive strength tests are listed in Table 42. The start and end of the single-leg drop jump was defined as the first and last points where ground reaction force reached 20N. The single-leg squat jump was defined as the point where ground reaction force reached 1.2 times bodyweight until the ground reaction force reached less than 20N. The measure of 'time from force increase to centre of mass movement' was the time from the start of the single-leg squat jump to the point where centre of mass power was greater than zero. The start and end of the single-leg drop landing was defined as the point where the ground reaction force first reached greater than 20N to the point where the vertical centre of mass power first returned to zero. Deceleration time was defined as the period of the single-leg drop landing.

Vertical rates of force development and impulses for the cuts and SL drop jumps were taken over the first 25ms and 50ms of eccentric and concentric phases and 25%, 50%, 75% and 100% of ground contact. For the other tasks, rates of force development and impulses were taken over the first 25ms and 50ms of the defined movement. The reactive strength index was calculated by dividing jump height by contact time. Stiffness was calculated as the ground reaction force at the end of the eccentric phase divided by the centre of mass displacement from the start of the movement to the end of the eccentric phase. Jump heights were calculated as the difference in vertical centre of mass height at toe off and the maximum vertical centre of mass height.

Additionally, in the cuts, 25ms and 50ms rate of force development and impulse for eccentric and concentric were calculated in each of the three planes. Also in the cuts, impulses over the first 25ms and 50ms of eccentric and concentric phases across all three planes and in the combined horizontal planes were summed. Ratios between the vertical and combined horizontal impulses were calculated for the whole ground contact and in the eccentric and concentric phases. Finally, peak forces in all three planes and total, eccentric and concentric ground contact times were calculated. The timings up to 50ms were selected as the minimum length of time for an eccentric phase was 50ms. The cut was defined as the points where the vertical ground reaction force first went above and lastly went below 20N. The eccentric phase was defined from the start of the cut to when the centre of mass power reached zero and the concentric phase being from then onwards. Performance outcome in the cuts was defined as time from passing the first timing gate to the second.

Table 42: Variables of interest for tests of reactive, explosive and maximum strength. Check marks indicate which variables were analysed for each test

Variable	**SL drop jump**	**SL squat jump**	**SL drop landing**	**IMTP**
Concentric V RFD 25 and 50ms	✔	✔		✔
Concentric V Impulse 25, 50 ms	✔	✔		✔
Eccentric V RFD 25 and 50ms	✔		✔	
Eccentric V Impulse 25, 50 ms	✔		✔	
V Impulse at 25, 50, 75, 100% of defined movement	✔		✔	
Peak vertical force	✔	✔	✔	✔
Peak vertical power	✔	✔	✔	
Time of force increase to CoM movement		✔		
Vertical stiffness	✔		✔	
Jump height	✔	✔	✔	
RSI	✔			
Ground contact time	✔			
Deceleration time			✔	

SL – Single-leg, IMTP – Isometric Mid-Thigh Pull, RFD - Rate of Force Development, V - Vertical, CoM - Centre of Mass, RSI - Reactive Strength Index

Statistical analysis

To reduce the high number of variables, a data reduction technique, Principal Component Analysis (PCA), was used to identify and examine patterns of variation in the cutting data as well as each of the 5 performance tests. Before applying the PCA discrete measures were centred (subtraction of mean) and normalised (division of standard deviation) (Joliffe, 1986). To solely examine key variables of a pattern, all PCA loadings below 75% of the absolute maximum were zeroed. While this made principal components non-orthogonal, it simplified the interpretation and captures only the effects of features that affect the pattern of variation most which is similar to the idea of analysis of characterising phases (Richter *et al.*, 2014) but used within features. Principle component scores were then determined by calculating the inner product between principal component and a subject feature vector. A cut-off correlation (r value) of 0.4 was selected and deemed necessary to be observed on both limbs to report findings as relevant. This was adopted as it is necessary for athletes to cut using both limbs and it seemed reasonable to assume that the same kinetic variables should be relevant on each limb.

In order to understand the relationship between the identified principal components during each cut and performance test, and performance outcome during the cutting tasks, a Pearson Product Moment Correlation with an alpha level of .05 was adopted. Thresholds used were 0.1, 0.3 and 0.5 for small, moderate and large correlations, respectively (Hopkins *et al.*, 2009).

10.3 Results

The principal components within the cuts that demonstrated significant correlations with cut times with an r value of ≥ 0.4 on each leg are shown in Table 43. One principal component comprising of greater peak lateral force and lower vertical to horizontal impulse ratio showed bilateral correlations ≥ 0.4 with 45° cut performance. Two principal components (lower vertical to horizontal impulse ratio; greater vertical RFD and multi plane impulses at 25ms and 50ms) showed bilateral correlations ≥ 0.4 with 110° cut performance.

Table 43: Significant principal components across each cut and their relationship with cutting performance outcome.

Exercise	Principal component	*r* value (CI) left	*r* value (CI) right
45° cut	Higher concentric and eccentric horizontal to vertical impulse ratio	-0.46 (-0.77 to 0.02)	-0.51 (-0.78 to -0.05)
110° cut	Higher concentric and eccentric horizontal to vertical impulse ratio	-0.70 (-0.86 to -0.42)	-0.62 (-0.81 to -0.29)
110° cut	25ms and 50ms vertical RFD; 25ms and 50ms vertical, resultant of vertical and lateral and summed vertical and lateral impulses	-0.44 (-0.71 to -0.03)	-0.44 (-0.71 to -0.05)

RFD – rate of force development, CI – confidence interval

The PCA identified two principal components (Table 44) with correlations ≥ 0.4 with performance outcome in either cut. These were within the single-leg drop jump (greater RSI and jump height) and within the single-leg drop landing (greater impulse over the first 25ms), and they correlated with the 110° cut performance outcome only. No principle components identified within the single-leg squat jump showed bilateral correlations with performance outcome in the cuts. Post hoc correlational analysis revealed strong correlations (*r* = 0.51 to 0.75) with performance outcome in both cuts on both legs.

Table 44: Significant principal components from tests of maximum, reactive and explosive strength and their relationship with cutting performance outcome.

Exercise	Principal component	*r* value (CI) left	*r* value (CI) right
SL drop jump with 110° cut	RSI, jump height	-0.54 (-0.77 to -0.19)	-0.51 (-0.75 to -0.14)

performance outcome			
SL drop landing with 110° cut performance outcome	Impulse over the first 25ms	0.49 (-0.06 to 0.81)	0.70 (0.21 to 0.91)

SL – single-leg, RSI – reactive strength index, RSI – reactive strength index

10.4 Discussion

The primary aim of the current study was to determine the ground reaction force features in cutting related to performance outcome in different angled cuts. Only one principal component identified within the 45° cut, associated with horizontal force production, demonstrated correlations ≥ 0.4 on each leg with performance. This component was comprised of two variables; greater peak lateral force and greater horizontal to vertical impulse ratio.

Two principal components were identified within the 110° cut showing correlations ≥ 0.4 on each leg with performance outcome. One of these was associated with greater horizontal to vertical force production and the other with greater vertical RFD and multi plane impulses during the first 50ms. This, in part, confirms the hypothesis that rapid force production is important for cutting but only in the 110° cut. What is apparent though, is that for both angles of cut, the ability to produce a greater proportion of force horizontally, is important for better performance outcomes. This finding is similar to those seen elsewhere in relation to cutting (Havens and Sigward, 2015a; Dos'Santos *et al.*, 2016) and is in line with findings relating to straight line acceleration (Morin, Edouard and Samozino, 2011) that show greater horizontal to vertical force production ratios are important for enhanced acceleration performance outcomes. The current study lends weight to the idea that developing an athlete's ability to express force horizontally is an important component of cutting performance.

This is the first study to investigate impulses and rates of force development over specific time intervals in the concentric and eccentric phases. The results highlight that early force production is more relevant in cuts of greater angle that require greater braking forces. This is due to the observation that impulse during the first 50ms of the 110° cut was important for cutting performance outcome, but not during the 45° cut. It is possible that the force demands to alter direction with only one step prior to the plate in the 45° cut were such that the greater proportion of horizontal force production and shorter ground contacts are more relevant than the amount of force produced during the first 50ms of ground contact in this task. Also of interest is that it was only the impulses during the first 50ms of ground contact and not during the first 50ms of the concentric phase that formed principal components in the 110° cut. It is possible that the increased deceleration demands in a greater angle cut (Havens and Sigward, 2015c) increased the emphasis on early force development. Elsewhere, vertical impulses over the whole eccentric phase, which did not form part of the identified principal components in the current study, have shown mixed correlations across cuts of different angles (Spiteri *et al.*, 2015) and peak vertical forces during the eccentric phase (Dos'Santos *et al.*, 2016) showed moderate to large correlations with performance outcome in 180° cuts. The strong correlations observed (r = 0.51 to 0.75) between shorter ground contact times and performance also support the notion that applying that force to the ground rapidly is necessary for enhanced performance outcomes.

The secondary aim of the current study was to understand the relationship between ground reaction force features in a series of maximum strength, explosive strength, reactive strength and deceleration tests and cutting performance outcome. The hypothesis that rapid force production qualities within each measure of maximum strength, explosive strength and reactive strength also correlate with cutting performance outcome was found to be incorrect. Only the single-leg drop jump and single-leg drop landing had principal components that showed correlations ≥ 0.4 on each leg with performance in the 110° but not the 45° cut. Within the single-leg drop jump, this principal component contained two variables; reactive strength index and jump height, while the principal component within the single-leg drop landing was made up of only one variable;

impulse over the first 25ms. The 45° and 110° cut were selected as they presented different challenges to the athlete. Cuts of greater angle have been shown to require greater braking forces than shallower angle cuts (Havens and Sigward, 2015c). This difference may explain why some relationship was seen between the single-leg drop landing impulses, where the athlete was cued to decelerate as quickly as possible, and performance outcome in the 110° cuts. However, this relationship may also indicate the influence of neural factors across tasks rather than a decelerative ability. Early rate of force development has been defined as force production in time periods under 100ms (Andersen *et al.*, 2010) with force production related to larger surface electromyography signals prior to initiation of torque development and observed to be predominantly driven by neural factors (de Ruiter *et al.*, 2004; Andersen and Aagaard, 2006; Folland, Buckthorpe and Hannah, 2014). Therefore, it is possible that the rapid force production observed in the drop landing and the 110° cut represents an ability to pre-activate muscle prior to ground contact which has been reported to modulate for stiffness during cutting tasks (Serpell *et al.*, 2014). Further work is needed to clarify this relationship.

Reactive strength, or the ability to utilise the stretch shortening cycle by rapidly moving from an eccentric to a concentric action (Young, 1995), has been shown elsewhere (Young, James and Montgomery, 2002; Delaney *et al.*, 2015; Young, Miller and Talpey, 2015; Maloney *et al.*, 2016) to correlate significantly with cutting performance outcomes. In the current study however, this correlation was only seen with the 110°, but not the 45° cut. It is possible that this is due to the differing demands of the two cutting tasks. The 45° cut, was organised with one step in the approach to bias accelerative components and may have removed the eccentric components to an extent that reactive strength qualities were irrelevant. This reduced role of the stretch shortening cycle, alongside the potential role of pre-activation discussed above, may be demonstrated in the lack of relationship observed between impulses over the first 50ms and 45° cut performance outcomes.

With the enhanced emphasis on acceleration in the 45° cut, it is surprising that, given strength has been reported to have significant correlations with acceleration in field sports athletes (Nimphius, McGuigan and Newton, 2010; Swinton *et al.*, 2014; C Thomas *et al.*, 2015) and with cutting performance (Negrete, R., Brophy, 2000; Peterson, Alvar and Rhea, 2006; Jones, Bampouras and Marrin, 2009; Nimphius, McGuigan and Newton, 2010; Spiteri *et al.*, 2014; Delaney *et al.*, 2015; Thomas, Dos'Santos, *et al.*, 2016), no ≥ 0.4 correlations were found in the isometric mid-thigh pull that was used to measure maximum strength. It is difficult to suggest a reason why this occurred in this instance, however, given the finding that horizontal rapid force production is important for enhanced cutting performance outcome, it is possible that peak force as measured with the isometric mid-thigh pull has limited transferability to cutting performance outcome. The lack of relationship between ground reaction force based variables within the single-leg squat jump suggest that these tests have limited ability as performance measures relevant to cutting performance outcome.

For the practitioner, relating these effect sizes from variables and its relevance for performance can be difficult. For context, the 45° cut range was 0.82s to 1.15s meaning an average speed range of $4.87 m.s^{-1}$ and $3.47 m.s^{-1}$. This means that over a second, there is a 1.4m difference between the fastest and the slowest participant. In the 110° cut, the range was 0.75s to 1.15s meaning an average speed range of $5.33 m.s^{-1}$ and $3.47 m.s^{-1}$. This means that over a second, there is a 1.86m difference between the fastest and the slowest participant. When considering Gaelic football, this distance difference would be easily enough to step past the outstretched arm of a tackler.

Some readers may consider it a limitation that in the current study we used a cut-off correlation of ≥ 0.4 on both limbs for variables that demonstrated relationships with performance outcome. This potentially ignores the effect of limb dominance on the strategy for completing the task. The decision was taken however to look for consistent relationships across both limbs on the assumption that the same variables contribute to faster times on both legs. Another limitation is that variables with loading less than 75% within the PCA were zeroed potentially ignoring important factors. An example of this is ground contact time which has shown consistent correlation with performance outcome (Sasaki *et al.*, 2011; Marshall *et al.*, 2014; Dos'Santos *et al.*, 2016) but did not associate with performance within the current PCA. Post hoc correlational analysis revealed strong correlations (r = 0.51 to 0.75) with performance outcome in both cuts on both legs. Due to the logistics of bringing athletes into the biomechanics laboratory for testing, it was not possible to utilise a separate familiarisation session. It is recognised that a lack of familiarisation may reduce the likelihood of achieving an absolute maximum performance in testing. However, all of those included in the study had a minimum training age in the gym of two years with programs including heavy strength training, jumping and cutting training which would limit the impact of a lack of familiarisation trials. Further, this approach has been taken elsewhere in the biomechanical analysis of cutting (Spiteri *et al.*, 2014; Rouissi *et al.*, 2016).

10.5 Conclusion

Of importance is that the ability to cut quickly is dependent on the ability to produce large amounts of horizontal force rapidly. This finding should be considered by coaches selecting exercises with the aim of improving cutting performance. Also of note is that the results of the current study demonstrate unexpectedly few relationships between kinetic variables from performance tests of reactive strength, explosive strength and maximum strength and cutting performance outcome. Given that the current study highlights that rapid horizontal force production, indicative of explosive strength, is important in cutting performance, it is possible that these qualities are task specific. Care should therefore be taken when interpreting findings from performance testing and selecting testing batteries relevant to cutting performance outcomes. Future research should seek to determine the effect of interventions on these variables to determine if performance can be achieved either through training of the qualities observed in the jumps are to determine if specific cutting training is more effective in improving performance

11 Principal component analysis of the biomechanical factors associated with performance during cutting

11.1 Introduction

The ability to change direction (cut) quickly is an important part of multi-direction sports (Spiteri *et al.*, 2017) with technique being one important component of performance (Young, James and Montgomery, 2002). To aid practitioners in developing training practices that enhance cutting performance, it is necessary to understand the relevant technical factors that contribute to performance. Only three other studies appear to have investigated joint-based biomechanical factors in relation to cutting performance (Sasaki *et al.*, 2011; Marshall *et al.*, 2014; Havens and Sigward, 2015a).

The technique of a cut is a combination of biomechanical and neuromuscular factors (Spiteri *et al.*, 2017). While a large number of biomechanical variables have been associated with better performance outcomes, their volume and variety makes the interpretation of results, and consequently their implementation into training practices difficult. The variety of significantly correlated examined biomechanical variables is exemplified by the following two studies: Marshall et al. (Marshall *et al.*, 2014) found that maximum ankle power (r = 0.77), maximum ankle plantar flexor moment (r = 0.65), pelvic lateral tilt (r = -0.54), maximum thorax rotation angle (r = 0.51) and ground contact time (r = -0.48) during the whole ground contact correlated with enhanced performance outcome in a 110° cutting task; while Havens & Sigward (Havens and Sigward, 2015a) found peak ankle flexor moment (r = 0.45), greater hip sagittal plane hip power (r = -0.48), lower hip extensor moment (r = 0.39) and greater peak medial-lateral centre of mass and centre of pressure separation (r = -0.39), greater medial lateral impulse (r = -0.49), greater hip internal rotation (r = -0.47), greater frontal plane hip power (r = -0.59) and lower knee extensor moments (r = 0.50) during the deceleration phase correlated with enhanced performance outcome in 45° and 90° cuts. In particular, this large number of variables is in contrast to coaching practice where limiting the number of factors for the athlete to focus on is believed to enhance skill acquisition (Singer, 1988; Raisbeck and Diekfuss, 2017), therefore reducing the number of variables may be beneficial. A secondary consideration for enhancing cutting performance is whether the angle of cut affects the joint-based biomechanical variables that contribute to performance. This is important to practitioners who may need to prioritise factors depending on cutting angles for particular sports or playing positions. Only Havens & Sigward (Havens and Sigward, 2015a) have measured joint-based biomechanical variables across different cutting angles with respect to performance. No common variables between the 45° and 90° cuts were found to significantly correlate with performance, however, only the decelerative phase (initial contact to peak knee flexion) of the cut step was considered.

A possible solution for reducing the large number of variables is to use a principle component analysis (PCA), a dimension reduction technique that allows a large number of variables to be reduced to a smaller number of uncorrelated underlying variables, or principal components (Jan Van Os and Meulman, 2012). While PCA has been employed in the domain area of biomechanics, for example in vertical jump (Charoenpanich *et al.*, 2013) and gait (Milovanovic and Popovic, 2012) analysis, it has yet to be performed on the joint variables in cutting. Grouping of related joint-based biomechanical variables may aid practitioners in identifying the biomechanical factors required to enhance performance outcomes in cutting.

Another possible limitation with the analyses used to date, is due to studies only using a mean measurement of a number of trials, thereby potentially removing important captured data and creating a 'trial' that does not represent any of the original attempts (Dufek *et al.*, 1995). As such, methods should be considered that allow for analysis of all of the captured data. Permutation testing is a method that takes repeated samples from the captured data (Bruce and Bruce, 2017) allowing analyses to be performed on greater amounts of captured data rather than the traditional method of creating a mean of the trials.

The main aim of the current study is to investigate the relationship between joint-based biomechanical variables in cutting and performance outcome across two different angled cuts, employing a PCA and permutation testing. It is hypothesised that there will be significant joint-based biomechanical principal components, allowing the reduction of the number of variables, and that some of these variables will be common across both angles of cut.

11.2 Methods

Twenty-five male (23.5 ± 4.2 years, 183 ± 6 cm, 83 ± 6.9 kg), elite Gaelic football players, all of whom train 4 to 6 times per week out of an invited 32 participated in the study.

Participants attended for testing on one occasion. Participants undertook a standardised warm up consisting of two minutes jogging, five forward, backward and lateral lunges on each leg, eight deep squats and five countermovement jumps. The first test performed was a 110° cut (Figure 22A) followed by a 45° cut (Figure 22B) on both limbs, with the limb testing order randomised but kept consistent across both tests. The 110° cut was selected as it requires a deceleration prior to the direction change which differs from the 45° which was selected as an accelerative cut. Two practice attempts were performed on each leg prior to each cut assessment to allow familiarisation. The 110° cut was as described previously (Marshall *et al.*, 2014) with the addition of timing gates (Fusion Sport Smartspeed, Queensland, Australia) positioned 1.5m apart at a height of 1.2m, two metres before and after the cutting point. For the 45° cut, the same timing gates were also set two metres before and after the cutting point with participants starting 30cm behind the timing gates in a staggered stance. The distance of two metres was chosen as it allowed only one ground contact prior to the cut to reduce the variety in strategies used during the cut. Participants were asked to repeat a trial if they used a drop step or felt their attempt was not maximum effort. For both cuts, trials were repeated if a full foot contact with the force plates was not achieved. Participants were instructed to complete all trials as quickly as possible.

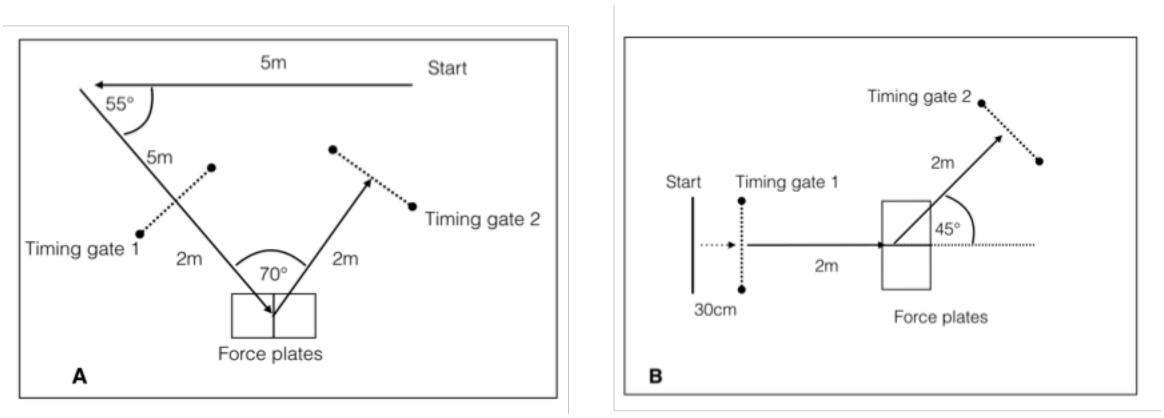

Figure 22: Layout for the A) 110° cut and B) the 45° cut

A ten-camera motion analysis system (Bonita B10, Vicon, UK), synchronised with two 40 x 60 cm force platforms (BP400600, AMTI, USA) was used to collect kinetic and kinematic data for all tests. Data were sampled at 200Hz and the Vicon Plug-in-Gait marker set was used as per Marshall et al (Marshall *et al.*, 2014). Twenty-four reflective markers were placed on bony landmarks at the lower limb, pelvis and trunk. Simultaneous kinematic and ground reaction force data (200Hz, 2000Hz) were collected using a software package (Nexus 2, Vicon Motion Systems, UK). These data were filtered using a fourth-order low-pass Butterworth filter (cut-off frequency 15Hz) (Kristianslund, Krosshaug and Bogert, 2013). The Vicon Plug in Gait modelling routine (Dynamic Plug in Gait) used standard inverse dynamics techniques to calculate segmental and joint kinetics (Winter, 2009).

Data Analysis

Variables of interest in all three planes were angles, angular velocities and moments about the ankle, knee, hip, pelvis and thorax; centre of mass distance to the ankle and the knee; and transverse plane foot to pelvis rotation angles. To allow comparison across cuts, data were time normalised to 100 data points. These variables were calculated for each discrete event which were identified (Figure 23) as impact, the change from the start to the end of the eccentric phase, the end of the eccentric phase, the change from the start to the end of the concentric phase and toe-off. Impact and toe-off were defined as the first and last points respectively where ground reaction force reached 20N. The end of the eccentric phase was defined as the point at which centre of mass power reached zero. The eccentric phase was identified therefore as the period from impact to the end of the eccentric phase, and the concentric phase from the end of the eccentric phase to toe-off. These events were identified for all of the cut trials for each participant prior to further analysis and resulted in a total of 200 variables.

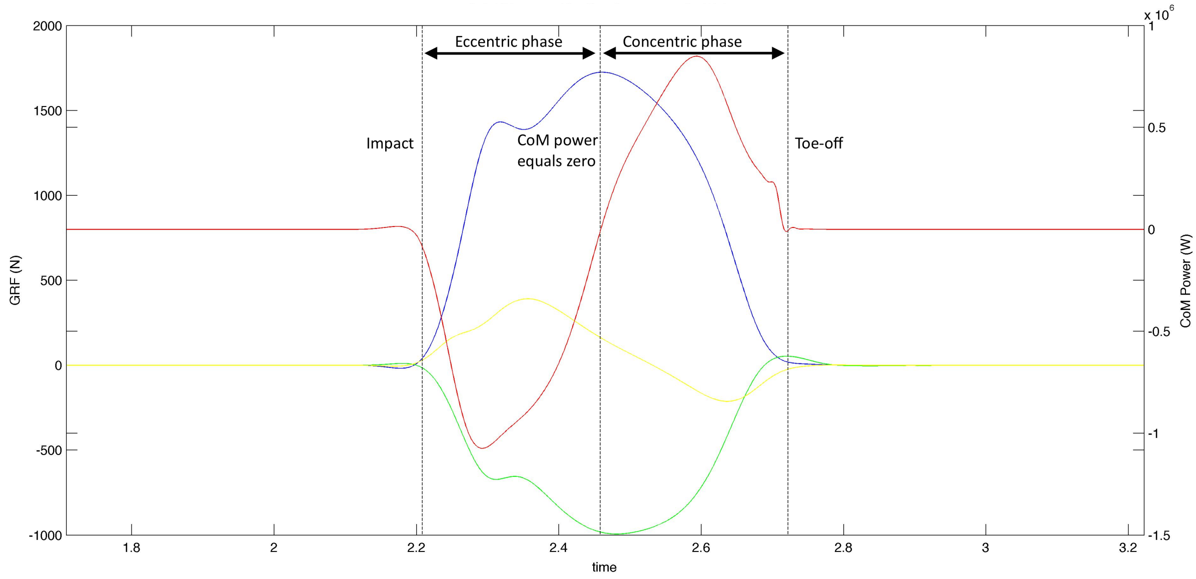

Figure 23: A force time curve of a 45° cut. Blue line - vertical GRF, green line - lateral GRF, yellow line - anterior/posterior GRF, red line - centre of mass power. GRF - Ground reaction force, CoM - Centre of mass

Analysis was comprised of two aspects; a principal component analysis (PCA) and a common correlation analysis using the discrete measures (Figure 24). A PCA was employed to identify patterns of variation within the cutting data. Before performing the PCA, features within the cutting data were centred (subtraction of mean) and normalised (division of standard deviation) to account for unit differences across the features within the data (Joliffe, 1986). All PCA loadings below 75% of the absolute maximum were zeroed to ensure variables that had the greatest contribution to the pattern were examined (Thorpe *et al.*, 2016). While this approach removed the orthogonal nature between principal components, it simplifies the interpretation and results in that only the effects of the features that have a large effect on the pattern of variation are included. Principle component scores were then calculated as the inner product between the principal component and the subject feature vector. Following the PCA, a simulation approach was then employed in the analysis of the identified principle components. A sample of 25 cuts, out of all of the cuts captured, was selected at random and a Pearson Product Moment Correlation was used in order to test the relationship between the identified principal component and cutting performance outcome. Thresholds used to judge the effect of a measure were 0.1, 0.3 and 0.5 for small, moderate and large correlations respectively (Hopkins *et al.*, 2009). The cuts were selected from both limbs as it is necessary for athletes to cut off both legs and the assumption was made that the same biomechanical variables should be relevant to performance on each limb. The permutation testing was performed by completing this random selection of 25 cuts with a Pearson Product Moment Correlation a total of 100 times. The factors within the relevant principle components were considered and grouped if they were deemed to be similar. These were then assigned a performance cue to describe those factors, for example if (a) 'lower vertical centre of mass to foot distance' and (b) 'lower centre of mass to knee distance' were observed within a principal component they were interpreted as 'maintaining a lower centre of mass'

A standard correlation analysis using the discrete measures was then performed to allow comparison with previous studies investigating the relationship between joint-based biomechanical variables and cutting performance outcome, all of which have used this approach. Additionally, due to the emphasis on variation and the 75% cut-off for loadings within the PCA, there was potential for missed relevant variables with lower levels of variation which is why a standard correlation analysis using the discrete measures was also employed. Using the same methodology as with the PCA, a sample of 25 cuts, out of all the cuts captured, was selected at random and a Pearson Product Moment Correlation was used in order to test the relationship between discrete measures and cutting performance outcome. The same permutation testing was then also completed 100 times. For both the principle components and the standard correlation analysis, an association to performance was considered to be relevant when a correlation measure appeared either positive or negative for greater than or equal to 95% of the random permutations. Variables from the standard correlation analysis were ranked based on their mean correlation in order identify the variables with the strongest effect on time to complete the cut.

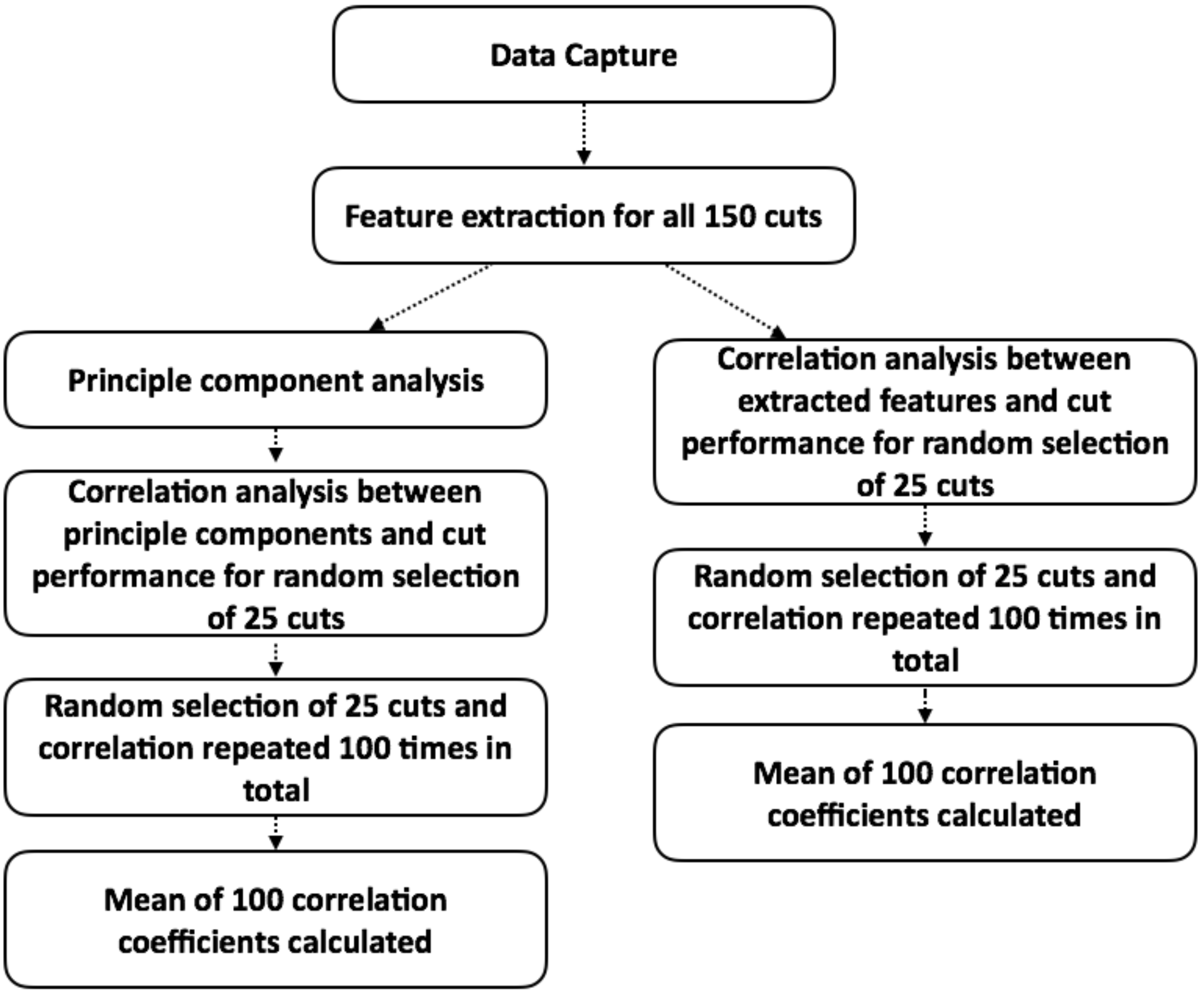

Figure 24: Flow chart of data processing and simulation

11.3 Results

Within the 45° cut one principal component demonstrated consistent correlations (mean r = 0.26) with performance outcome in greater than or equal to 95% of the permutations analysed (Table 45). This component was made up of twelve factors: eccentric lateral centre of mass to knee distance change, lateral centre of mass to ankle distance at impact and end of eccentric phase, concentric vertical centre of mass to ankle distance, concentric knee flexion angle change, hip flexion angles at end of eccentric and change in through concentric phase, knee flexion angular velocity at end of eccentric, hip flexion angular velocity at the end of eccentric phase and change through concentric phase and total and concentric ground contact times.

Within the 110° cut, two principal components demonstrated consistent correlations with performance outcome in greater than or equal to 95% of the permutations performed (Table 46). The first principal component (mean r = 0.66) was made up of thirteen factors: Lateral centre of mass to knee distance at end of and change through eccentric phase, concentric vertical centre of mass to knee distance change, lateral centre of mass to ankle distance at end of eccentric, posterior centre of mass to ankle distance at end of eccentric, concentric vertical centre of mass to ankle distance change, hip flexion angles at end of eccentric and concentric and eccentric change, pelvis abduction angles at toe-off, pelvis flexion angles at end of eccentric and total and concentric ground contact times. The second principal component (mean r = 0.27) was made up three factors: Thorax to pelvis abduction angles at impact and toe-off and thorax to pelvis rotation angular velocity at toe-off.

In relation to the standard correlation analysis, the ten strongest individual correlations between kinematic variables within the 45° cuts and performance outcome are listed in Table 43 and placed in order of correlation strength. The correlations with performance outcome are all moderate (r = -0.41 to -0.33 and 0.34 to 0.40). Four variables relate to the ankle (rows 1, 2, 4 and 10), two variables relate to horizontal movements (row 6 and 7), one variable relates to staying low during the concentric phase (row 3), one variable relates to ground contact time (row 8), one variable relates to knee rotation (row 9) and one to rotating the torso in the direction of the cut (row 5) (Table 47).

The ten strongest correlations between kinematic variables within the 110° cuts and performance outcome are listed in Table 4 and placed in order of correlation strength. The correlations with performance outcome are all strong (r = -0.66 to -0.56 and 0.53 to 0.62). Three of the variables relate to maintaining lateral ankle and knee distances through the eccentric phase (rows 2, 4 and 8), three are related to resisting sagittal plane flexion movements during the eccentric phase (rows 6, 9 and 10), two are related to shorter ground contact times (rows 5 and 7), and two are related to a toe off position with greater pelvis abduction and less distance between the centre of mass and the ankle posteriorly (rows 1 and 3) (Table 48).

Table 45: Principal components with positive of negative correlations in ≥ 95% of the simulated 45° cuts

Principal component interpretation	**Principal Component factors (loadings)**	***r* value (CI)**
Maintaining a low centre of mass during the concentric phase	Vertical CoM to ankle distance change through conc phase (0.16)	0.26 (0.23 to 0.29)
Shorter ground contact times	Conc phase ground contact time (0.17), total ground contact time (0.14)	
Faster and larger extensions of the hip and knee	Knee flexion angular velocity at end of ecc phase (0.15), hip flexion angular velocity change through conc phase (-0.15), hip flexion angular velocity at end of ecc phase (0.14), knee flexion angles change through conc phase (-0.15), hip flexion angles at end of ecc phase (0.17), hip flexion angles change through conc phase (-0.17).	
Resisting a reduction in lateral centre of mass to ankle and knee distance in the eccentric phase	Lateral CoM to ankle distance at end of ecc phase (0.17), lateral CoM to knee distance change through ecc phase (-0.13), lateral CoM to ankle distance at impact (0.13)	

Ecc - eccentric, conc - concentric, CoM - centre of mass

Table 46: Principal components with positive of negative correlations in ≥ 95% of the simulated 110° cuts

PC	Interpretation	Principal component factors (loadings)	*r* value (CI)
1	Maintaining a low centre of mass during the concentric phase	Vertical CoM to knee distance change through conc phase (0.13), vertical CoM to ankle distance change through conc phase (0.13), pelvis abduction angles at toe-off (-0.12),	0.66 (0.65 to 0.68)
	Resisting hip flexion then using hip extension	Hip flexion angles at end of ecc phase (0.16), hip flexion angles change through ecc phase (0.15), pelvis flexion angles at end of ecc phase (0.12), hip flexion angles change through conc phase (-0.15),	
	Resisting a reduction in lateral centre of mass to ankle and knee distance in the eccentric phase	Lateral CoM to knee distance change through ecc phase (-0.13), lateral CoM to ankle distance at end of ecc phase (-0.13), posterior CoM to ankle distance at end of ecc phase (0.13), lateral CoM to knee distance at end of ecc phase (-0.15),	
	Shorter ground contact times	Conc phase ground contact time (0.14), total ground contact time (0.14).	
2	Lean in direction of the cut	Thorax to pelvis abduction angles at toe-off (-0.21), thorax to pelvis abduction angles at impact (-0.18), thorax to pelvis rotation angular velocity at toe-off (0.18)	0.27 (0.24 to 0.30)

Ecc - eccentric, conc - concentric, CoM - Centre of mass, PC – principal component

Table 47: The 10 variables with the strongest correlations to performance during 45° cut grouped by phase of the cut.

Order	**Variable**	**Time point**	**Range**	**Mean ± st dev**	***r* value (CI)**	**Interpretation related to faster times**
1	Ankle rotation angles (°)	Change from the start to the end of the eccentric phase	-17.09 to 26.53	0.52 ± 7.70	-0.41 (-0.44 to -0.39)	Less external rotation change
2	Ankle abduction angles (°)	Change from the start to the end of the eccentric phase	-7.00 to 4.89	-0.14 ± 2.04	0.40 (0.37 to 0.43)	Greater abduction change
3	Vertical centre of mass to ankle distance (mm)	At toe-off	267.74 to 366.74	325.14 ± 0.02	0.37 (0.34 to 0.39)	Lower distance between centre of mass and ankle
4	Ankle abduction angles (°)	Change from the start to the end of the concentric phase	-8.40 to 3.49	-2.90 ± 2.31	-0.37 (0.37 to 0.43)	Smaller change in ankle abduction
5	Thorax to pelvis rotation angles (°)	At end of eccentric phase	-15.28 to 19.19	-2.43 to 5.41	0.36 (0.34 to 0.39)	Greater contralateral thorax rotation angle

6	Hip abduction angles (°)	Change from the start to the end of the eccentric phase	17.31 to 12.56	-4.63 ± 5.54	0.36 (0.33 to 0.39)	Smaller change in hip abduction
7	Posterior centre of mass to knee distance (mm)	Change from the start to the end of the concentric phase	112.87 to 425.88	278.85 ± 55.44	0.35 (0.32 to 0.39)	Smaller change in distance throughout phase
8	Ground contact time (s)	Change from the start to the end of the concentric phase	0.07 to 0.20	0.12 ± 0.02	0.34 (0.31 to 0.37)	Shorter ground contact time
9	Knee rotation angles (°)	Change from the start to the end of the eccentric phase	-22.82 to 15.04	3.71 ± 6.53	0.34 (0.30 to 0.37)	Smaller change in knee rotation
10	Ankle rotation angles (°)	At end of eccentric phase	-41.2 to 4.5	-20.89 ± 11.07	-0.33 (-0.36 to -0.30)	Straighter foot position

St dev - standard deviation, CI - confidence interval, CoM - Centre of Mass

Table 48: The 10 variables with the strongest correlations to performance during 110° cut grouped by phase of the cut.

Order	**Variable**	**Time point**	**Range**	**Mean ± St dev**	***r* value (CI)**	**Interpretation related to faster times**
1	Pelvis abduction angles (°)	At toe-off	-0.46 to 40.6	23.30 ± 6.54	-0.66 (-0.69 to -0.64)	Greater pelvis abduction angles
2	Lateral centre of mass to ankle orientation (mm)	End of eccentric phase	267.90 to 625.23	453.23 ± 67.27	-0.65 (-0.67 to -0.63)	Greater distance between the ankle and centre of mass
4	Lateral centre of mass to knee orientation (mm)	End of eccentric phase	129.34 to 406.18	247.40 ± 52.71	-0.63 (-0.64 to -0.61)	Greater lateral distance between knee and centre of mass
3	Posterior centre of mass to ankle orientation (mm)	At toe-off	215.63 to 380.94	298.47 ± 27.17	0.62 (0.60 to 0.64)	Lower posterior distance between ankle and centre of mass
5	Ground contact time (s)	At toe-off	0.24 to 0.49	0.30 ± 0.03	0.60 (0.58 to 0.62)	Shorter ground contact time
6	Hip flexion angles	Change from the start to the	-33.90 to 20.46	-5.09 ± 11.44	0.59 (0.57 to 0.60)	Less hip flexion change

		end of the eccentric phase				
7	Time (s)	Change from the start to the end of the concentric phase	0.06 to 0.31	0.20 ± 0.05	0.58 (0.56 to 0.60)	Shorter concentric time ground contact time
8	Lateral centre of mass to knee orientation (mm)	Change from the start to the end of the eccentric phase	-92.26 to 132.48	18.44 ± 40.75	-0.56 (-0.58 to -0.53)	Greater change in distance
9	Hip flexion angles (°)	End of eccentric phase	7.66 to 86.79	-53.73 ± 15.06	0.54 (0.52 to 0.56)	Greater hip extension
10	Thorax to pelvis flexion angles (°)	End of eccentric phase	-59.13 to 4.47	-32.08 ± 10.04	0.53 (0.51 to 0.55)	Less thorax to pelvis flexion

St dev - standard deviation. CI - Confidence interval. A/P - anterior posterior

11.4 Discussion

The main aim of the current study was to investigate the relationship between joint-based biomechanical variables in cutting and performance outcome across different angled cuts. To that end, a principal component analysis was employed to reduce the volume of variables by grouping them through common patterns of variation. This is the first study to take this approach with respect to joint-based biomechanics of cutting.

One principal component was identified as being relevant to describe performance outcome within the 45° cut instead of 29 relevant individual variables identified during the standard correlation analysis. This principal component was interpreted as being comprised of four performance cues: maintaining a low centre of mass during the concentric phase, utilising a shorter ground contact time, resisting a reduction in lateral centre of mass to ankle and knee distance in the eccentric phase and utilising faster and larger extensions of the hip and knee (Table 45).

Two principal components were identified as being relevant to describe performance outcome within the 110° cut instead of 85 relevant individual variables identified during the standard correlation analysis. The first principal component was interpreted as being comprised of four performance cues: maintaining a low centre of mass during the concentric phase, utilising a shorter ground contact time, resisting a reduction in lateral centre of mass to ankle and knee distance in the eccentric phase and resisting hip flexion then using hip extension (Table 46). The second principle component was interpreted as represented by one performance cue: leaning in the direction of the cut.

Three performance cues were common across both the 45° and 110° angles of cut: maintaining a low centre of mass during the concentric phase, resisting a reduction in lateral centre of mass to ankle and knee distance in the eccentric phase and utilising a shorter ground contact time. Findings from previous studies that employed standard correlation analyses corroborate the findings in the current study where the performance cue of shorter ground contact times was correlated with better cutting performance outcomes (Sasaki *et al.*, 2011; Marshall *et al.*, 2014; Dos'Santos *et al.*, 2016). Also, the performance cue of maintaining lateral centre of mass to ankle and knee distance in the eccentric phase observed in the current study suggests similarities with the findings of Havens and Sigward (Havens and Sigward, 2015a) who found greater peak lateral separation between centre of mass and foot placement during the deceleration phase was significantly correlated (r = -0.47) with cut performance outcome in a 45° cut. Finally, similar to the current findings, Shimokochi et al (Shimokochi *et al.*, 2013) observed that maintaining a lower centre of mass at both initial contact and at the end of the eccentric phase correlated with a higher cutting index, which they used as a performance measure, during a lateral cutting task.

While there is commonality across the three cuts, a contrast was also observed with each angle of cut having one performance cue that was not shared; resisting hip flexion then using hip extension in the 110° cut and utilising faster and larger extensions of the hip and knee in the 45° cut. This is likely due to the differing demands of the task. The 110° cut highlighted the requirement to resist hip flexion movements prior to utilising greater hip extension, potentially related to the greater decelerative demands of cuts of greater angle (Havens and Sigward, 2015c), while the faster and larger hip and knee extensions observed within the 45° cut principal component may be reflective of the accelerative demands of the task (Havens and Sigward, 2015c). While a degree of commonality exists in the performance determining biomechanical factors between the cuts of different angles, task specific demands/factors are also apparent.

For the practitioner, relating these effect sizes from variables and its relevance for performance can be difficult. For context, the 45° cut range was 0.82s to 1.15s meaning an average speed range of 4.87m.s^{-1} and 3.47m.s^{-1}. This means that over a second, there is a 1.4m difference between the fastest and the slowest participant. In the 110° cut, the range was 0.75s to 1.15s meaning an average speed range of 5.33m.s^{-1} and 3.47m.s^{-1}. This means that over a second, there is a 1.86m difference between the fastest and the slowest participant. When considering Gaelic football, this distance difference would be easily enough to step past the outstretched arm of a tackler.

The principal component analysis was utilised to reduce a large number of variables to a smaller group of variables that explained performance, the performance cues were used to further interpret the principal components for the practitioner. However, it is not possible to state that all of the discussed performance cues have the same level of importance or that they are exclusive of each other. For example, it is possible that utilising a shorter ground contact time to enhance performance is achieved by maintaining a low centre of mass during the concentric phase with faster and larger hip and knee extensions and resisting a reduction in lateral centre of mass to ankle and knee distance in the eccentric phase. This raises the question of whether one of these performance cues can elicit a greater effect on cutting performance than the others. A further body of work is required to determine the relationship that exists between these performance cues and to determine if training to enhance any one of them is more effective at enhancing performance than the others.

Finally, it is worth noting that the principle components were only able to explain 43% and 7% of the variance within the 110° cut and 7% of the variance in the 45° cut. It is likely therefore that other factors, such as neuromuscular capacity, help to explain the remaining variance in performance. It is also possible that the task demands of the 45° cut employed in the present study, with having only one step prior to the cut, meant that joint-based biomechanical factors played a smaller role and neuromuscular capacity was more important for performance than was observed in the 110° cut. Additionally, the relatively small effect sizes observed could be due to a number of reasons. A greater number of faster or slower trials could skew the analysis effecting reducing the sizes of the correlations observed. Alternatively, it may be that different technique profiles or strategies exist for faster and slower performers. Future work should consider the use of cluster analysis to determine if this is the case (Franklyn-Miller *et al.*, 2016).

One limitation of the current study is that the performance cues selected and used were an interpretation by the authors of the observed variables and it is possible that they could be interpreted in other ways not considered in the current study. Due to the logistics of bringing athletes into the biomechanics laboratory for testing, it was not possible to utilise a separate familiarisation session. It is recognised that a lack of familiarisation may reduce the likelihood of achieving an absolute maximum performance in testing. However, all of those included in the study had a minimum training age in the gym of two years with programs including cutting training which would limit the impact of a lack of familiarisation trials. Further, this approach has been taken elsewhere in the biomechanical analysis of cutting (Spiteri *et al.*, 2014; Rouissi *et al.*, 2016).

11.5 Conclusion

Of importance from the current study is that common factors exist between cuts of larger and shallower angles. Employing technical and physical training that seeks to develop the abilities and capacity to utilise shorter ground contact times, to maintaining a low centre of mass during the concentric phase, and to resisting a reduction in lateral centre of mass to ankle and knee distance in the eccentric phase should be considered. Coaches should also note however, that relationships likely exist between these performance cues and that by addressing one, all of them may be affected, but that further work is required to understand this interaction.

12 Discussion

12.1 Overall summary

It is recognised that deficits in maximum strength, explosive strength and deceleration are present in those rehabilitating from musculoskeletal conditions (Petersen *et al.*, 2014; Blackburn *et al.*, 2016; Pozzi *et al.*, 2017). It is also known that these qualities are important for performance (Cormie, Mcguigan and Newton, 2011; Havens and Sigward, 2015b; Suchomel, Nimphius and Stone, 2016). Reactive strength is another important performance based variable (Young, Miller and Talpey, 2015), however, there is little research investigating the role of reactive strength in rehabilitating populations. When considering maximum strength and explosive strength in those rehabilitating from musculoskeletal conditions, these are generally measured about a single joint. However, when considering athletic performance, measurements of maximum strength and explosive strength, alongside reactive strength and deceleration, are generally measured using whole-body movements. Furthermore, in active populations returning to sport, cutting is an important task due to its association with injury (Brown, Brughelli and Hume, 2014; Whittaker *et al.*, 2015) and for return to high levels of performance. The relationship between maximum strength, explosive strength, reactive strength and deceleration, and cutting had not, until this thesis, been examined. The main focus of this thesis was to examine the role of whole-body maximum strength, explosive strength, reactive strength and deceleration in rehabilitation and performance.

Study one examined the effects of a free-weight based, whole-body resistance training intervention in those with chronic low back pain. It was found that a 16-week free-weight resistance training intervention led to significant improvement in symptoms, a significant improvement in lumbar muscle endurance, a reduction in fat infiltration and an increase in the functional cross-sectional area of the lumbar paraspinal muscles. However, in disagreement with the hypothesis, no increase in maximum strength or explosive strength as measured by the isometric mid-thigh pull were observed. When considered with the observed improvement in lumbar muscle endurance, it is possible that lumbar muscle conditioning is more important than whole-body maximum strength and explosive strength. This has been suggested elsewhere with low back pain having been associated with reduced lumbar paraspinal strength and rate of force development (Steele, Bruce-Low and Smith, 2014a; Rossi *et al.*, 2017). This implies that maximum strength and explosive strength, as measured with the isometric mid-thigh pull, plays a limited role in the rehabilitation of those with chronic low back pain. These results led to the question of whether maximum strength, explosive strength and, additionally, reactive strength and deceleration are relevant in another chronic condition (athletic groin pain) in a group where these neuromuscular qualities are valued for performance. To answer this question, study two was undertaken.

Study two examined the differences in maximum strength, explosive strength, reactive strength and deceleration, alongside cutting performance in a group with athletic groin pain compared to a non-injured group. It was found that injured athletes demonstrated deficits across measures of maximum strength, explosive strength, reactive strength and deceleration. They also demonstrated poorer performance and poorer ability to rapidly produce force during cutting tasks. These results likely highlight a deconditioning as a result of pain inhibition (Harris-Hayes *et al.*, 2014) and reduced training volumes in an effort to manage pain (Neufer *et al.*, 1987; Holmich and Thorborg, 2014).

Given the deficits in explosive strength measures observed in study two, study three aimed to examine the effect of additional explosive strength training (in the form of additional weighted jumps) on maximum strength, explosive strength, reactive strength and deceleration, alongside cutting performance. It was found that this additional explosive strength training led to an altered cutting strategy with reduced ground contact times and greater levels of concentric explosive strength. These changes were observed alongside a faster return to play time and the same level of positive resolution of symptoms. This was the first study to examine the effects of additional explosive strength training in those rehabilitating from athletic groin pain. It is therefore suggested that explosive strength training should be included as part of rehabilitation from athletic groin pain due to its performance enhancing effects. Of importance is that measures of deceleration, reactive strength and explosive strength improved in both groups throughout their rehabilitation.

Together the first three studies examined the role of maximum strength, explosive strength, reactive strength and deceleration in rehabilitation. Studies four and five aimed to determine if the same qualities that impact rehabilitation from injury, are the same that contribute to performance during cutting. This is important in order to inform the design of training interventions for both performance and rehabilitation. To this end, they both utilised a unique approach with the use of a principal component analysis alongside a simulation approach. In study four, it was found that performance during the cut, in line with the literature on linear acceleration (Morin, Edouard and Samozino, 2011), was determined by the technical ability to produce a greater proportion of concentric horizontal force compared to vertical force during the cut. It was also found that greater levels of reactive strength, which corroborate findings elsewhere (Young, Miller and Talpey, 2015), and greater early deceleration ability also positively correlated with performance. Of note is that maximum strength was not correlated with performance which is in disagreement with the majority of the literature (Spiteri *et al.*, 2013; Swinton *et al.*, 2014; Delaney *et al.*, 2015). These findings highlighted that cutting performance is likely impacted by technical ability to produce force alongside neuromuscular strength capacity, meaning that practitioners should seek to develop both in efforts to enhance performance.

Study five aimed to determine the technical qualities that determine cutting performance through a kinematic analysis of the performance determinants of cutting. It was found that staying lower throughout the cut, utilising short ground contact times and maintaining lateral centre of mass to ankle distance were correlated with enhanced performance across two angles of cut. Staying lower throughout the cut (Shimokochi *et al.*, 2013), utilising short ground contact times (Marshall *et al.*, 2014; Dos'Santos *et al.*, 2016) and maintaining lateral centre of mass to ankle distance (Havens and Sigward, 2015a) have all been associated with performance elsewhere. These results will assist coaches in determining the key technical qualities for faster cutting to be implemented in training interventions.

12.2 Conclusions

This thesis highlights a number of important areas. While increases in whole-body maximum strength are not necessary for rehabilitation from low back pain, the use of whole-body free-weight resistance training can improve the conditioning of the lumbar musculature along with improvement in symptoms. In an athletic groin pain population, deficits in maximum strength, explosive strength, reactive strength and deceleration are present when compared with a non-injured population. The rehabilitation program of King et al (King *et al.*, 2018) was able to improve many of these variables alongside resolution of symptoms. The inclusion of additional explosive strength training as part of the rehabilitation program can reduce the time taken for this to occur, resulting in an earlier return to play. Finally the deficits observed during cutting tasks in those with athletic groin pain compared to non-injured populations are not the same variables that relate to faster cutting. The deficits observed in those with athletic groin pain likely relate to deconditioning of force production capacity whereas the factors related to cutting performance appear to be related to the technical ability to apply the force

For the practitioner, there are a number fo recommendations to be taken from this thesis. The first is that whole-body free-weight resistance training is advocated to improve the conditioning and force production capacity of those rehabilitating from chronic musculoskeletal conditions. That training interventions that seek to enhance maximum strength, explosive strength, reactive strength and deceleration abilities during the rehabilitation of athletic groin pain should be utilised and further explored. Further, given the deficits in performance observed in those with athletic groin pain, pracitioners should be cogniscent of that effect of performance and consider measures to determine whether performance has been restored upon return to play. Finally, when considering cutting performance practitioners should seek to develop the technical ability to produce force in the horizontal plane rather than relying on vertical explosive strength activities in training. When targeting technical changes to an athlete’s cutting, challenging an athlete’s ability to adopt lower centre of mass positions and maintaining the lateral distance between the foot and the centre of mass while utilising a short ground contact time should be prioritized.

12.3 Limitations

One limitation present in this thesis is related to the organisation of rehabilitation interventions. This thesis took two approaches: a one-size fits all approach with all participants performing the same intervention for a set period of time (Chapter 6) and an individulised progression of rehabilitation based on clinical testing (Chapter 8). While the latter is in line with clinical practice (Dhillon, Dhillon and Dhillon, 2017), it creates difficulty in interpretation of results due to differences between groups in the volume of exposure. More frequent testing throughout interventions may aid in the interpretation of results. For example, in chapter 8, performance testing and collection of outcome measures at the transition between the different levels of rehabilitation would give insight into the physical and symptom changes throughout the intervention. This would inform whether certain aspects of the rehabilitation are more important than others.

When interpretting the results of the studies within chapters 7 to 11, consideration should be given to the limitations discussed within each of those chapters. The lack of separate familiarisation testing throughout each of the studies may have meant that a true maximum performace may not have been achieved within the test. Further, for chapter 7 and chapter 9 both of which utilised multiple testing sessions, it is possible that without separate familiarisation sessions, a learning effect may have contributed to changes in performance across testing sessions.

Within chapter 7, the lack of a control group means that it is not possible to determine with any certainty that the changes observed occurred as a result of the intervention. These results, while promising, require further work through the use of a randomised controlled trial to determine the true effectiveness of the intervention in those with chronic low back pain.

Within chapter 9, the low numbers analysed and the different interventions employed when the participants were pooled (jumps and no-jumps) mean that interpration of these results should be seen as exploratory pilot work. However, there are indeed interesting observations that future work should test to determine the importance to the observed changes in variables in the rehabilitation of athletic groin pain.

12.4 Future research

Further work is required to determine if the intervention for those with low back pain in chapter 7 is effective when compared to or in combination with other common forms of rehabilitation. Given the between-group and between-limb differences observed in between those with and without athletic groin pain in chapter 8, further work should prospectively explore how these deficits develop over time. It should seek to determine if it is part of an athlete's normal state that predisposes them to the development of this condition or whether they develop these deficits over time in response to training or fatigue. Given the change in local lumbar strength/endurance observed in reponse to the low back pain intervention resulting in positive changes to outcome scores, similar work could be taken within an athletic groin pain cohort. Work should seek to examine the role of strength, fat infiltration and functional cross sectional area in musculature about the hip to determine the role of the conditioning of local musculature in rehabilitation from athletic groin pain. The observations from chapter 9 could serve as a basis to determine the effect of interventions. Testing more regularly throughout a rehabilitation intervention could aid in understanding of whether, as pain reduces, performance qualities are restored. For example, by testing cutting performance prior to the start of cutting training and taking more frequent HAGOS measures, it would be possible to determine if performance has been restored without specific training. This would allow either a streamlining of rehabilitation or an enhanced understanding of how performance is affected throughout the rehabilitation process.

In relation to cutting performance, exploration of methods to enhance the technical components of horizontal force production is required to assist coaches in the design of training interventions. Furthermore, measuring different types of cuts or even dummy cuts that are more sport specific will assist in determining if those same qualities observed are consistent across all types of cut.

13 Bibliography

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14 Appendices

14.1 Appendix 1: A comparison of quantitative computer base and qualitative visual analysis techniques for measuring changes in MRI-defined lumbar fat infiltration

14.1.1 Introduction

The causes of low back pain are multifactorial with physiological, genetic, psychological, social and patho-anatomical factors all thought to contribute (O'Sullivan, 2005). The relationship between physiological factors including lumbar paraspinal fat infiltration and cross sectional area and low back pain have been investigated using medical imaging techniques (Demoulin, Crielaard and Vanderthommen, 2007). Using these techniques, higher levels of lumbar paraspinal fat infiltration have been associated with low back pain (OR = 9.2; 25 to 48% difference compared to healthy controls) (Parkkola, Rytökoski and Kormano, 1993; Mengiardi *et al.*, 2006; Kjaer *et al.*, 2007). Both reduced muscle cross sectional area and increased muscle fat infiltration are associated with loss of strength and increased fatigability (Boonyarom and Inui, 2006; Addison *et al.*, 2014). This forms part of a deconditioning hypothesis, made up of both increased lumbar paraspinal fat infiltration and reductions in lumbar paraspinal muscle cross sectional area, that is a contributing factor in low back pain (Steele, Bruce-Low and Smith, 2014a).

The measurement of lumbar paraspinal fat infiltration involves the analysis of Magnetic Resonance Images (MRI) or Computer Tomography scans. Both visual qualitative (Mengiardi *et al.*, 2006; Kjaer *et al.*, 2007) and quantitative computer based analysis techniques (Lee *et al.*, 2008; De Sèze *et al.*, 2011; Le Cara *et al.*, 2014) have been used in the literature as methods of quantifying and categorising the degree of observed lumbar paraspinal fat infiltration. Qualitative visual analysis techniques involve assessment by a radiologist who assigns each scan to a category. These categories are usually descriptive based on how much fat there is relative to muscle, for example none, slight (10 to 50%) or severe (>50%)

(Kjaer *et al.*, 2007), and is therefore reliant on the skill and the experience of the radiologist in order assign scans to the correct category. Further, given how broad these categories are, they are limited in their sensitivity.

Quantitative computer based analysis techniques measure signal intensity using a histogram and set an appropriate threshold to allow differentiation between areas of fat and muscle. The number of pixels in the fatty regions are calculated as a percentage of the whole region of interest to give a percentage fat infiltration within the selected region (D'hooge *et al.*, 2012). Both qualitative visual and quantitative computer based analysis techniques have been shown to be reliable (Gorgey and Dudley, 2007; Akgul *et al.*, 2013). However, Mengiardi et al (Mengiardi *et al.*, 2006) found quantitative computer based analysis to be able to detect significant differences (25% to 48%) in lumbar paraspinal fat infiltration between those with and without low back pain, while qualitative analysis indicated no difference. This raises questions as to the accuracy of qualitative visual techniques in measuring lumbar fat infiltration. While this is the case comparing symptomatic and asymptomatic groups, it is as yet unknown whether or not such differences also exist in the ability of qualitative visual and quantitative computer based analysis techniques to detect changes in lumbar fat infiltration over time in response to a targeted exercise intervention.

The aim of the current study is to compare qualitative visual and quantitative computer based analysis techniques in measuring lumbar paraspinal fat infiltration prior to and after a free-weight based resistance training intervention in those with low back pain.

14.1.2 Methods

Participants had presented with low back pain symptoms lasting longer than three months to one of six Sports Medicine Consultants at a large sports medicine practice. All underwent clinical history and examination by a Sports Physician including MRI examination. Exclusion criteria were: previous spinal surgery, tumors, nerve root entrapment accompanied by neurological deficit, spinal infection, inflammatory disease of the spine and other disorders preventing active rehabilitation. Those who met the inclusion criteria were informed of the study, given an information leaflet and offered the opportunity to ask questions of the lead researcher. All participants completed and signed an informed consent form prior to partaking; the study met the approval of the Sports Surgery Clinic Hospital Ethics committee (25-EF-008).

Thirty participants, 11 females (age = 39.6 ± 12.4 years, height = 164 cm ± 5.3cm, body-mass = 70.9 ± 8.2kg,) and 19 males (age = 39.7 ± 9.7 years, height = 179 ± 5.9cm, body mass = 86.6 ± 15.9kg) between the ages of 16 and 60 were recruited. Four participants dropped out due to: an unrelated ankle injury (n = 1), not attending all testing sessions (n = 1), work commitments (n = 1) and a lack of adherence to the program (n = 1).

Lumbar spine MRIs were obtained at initial clinical assessment on entering the study and following a 16-week resistance training intervention. The majority of images were obtained using a 3 Tesla MRI system (GE Signa, General Electric Healthcare, USA). Five participants provided images completed on a 1.5 Tesla external MRI system as they had been referred by their GP for an MRI prior to attending an appointment with the Sports Medicine Consultant. Axial T2 weighted non-fat-saturated sequences were used for evaluation. Fat infiltration was measured at the lower end plate at the L3L4, L4L5 and L5S1 levels. For the quantitative computer based analysis, the region of interest was defined as the area of erector spinae and multifidus musculature (Lee *et al.*, 2008; Kong, Lim and Kim, 2014) and percentage fat infiltration was calculated for the total area using a standalone graphical user interface developed in Matlab R2010a (Antony *et al.*, 2015) (Figure 25). Using the centre of the vertebral body as a reference point, the region of interest was further subdivided into six regions based on distance from the vertebral body (Figure 26). Percentage fat infiltration was calculated for each of the sub-regions as well as the total region of interest. Qualitative visual analysis was performed by two radiologists with over five years of experience each. They graded fat infiltration as: 0, no intramuscular fat; 1, some fatty streaks; 2, less fat than muscle; 3, equal fat and muscle; 4, more fat than muscle (Mengiardi *et al.*, 2006). All scores from both radiologists were used in the analysis. Intra-user reliability in selecting the region of interest was tested using sixty images on two occasions, two days apart.

Statistical analysis

All values were reported as mean and SD (mean ± SD) and percentage change following intervention. All data were checked for normality using a Shapiro-Wilk test. To examine the level of agreement between the quantitative and the qualitative analysis techniques a regression was undertaken between the original quantitative measures and the predicted quatitative measures, with 95% limits of prediction (Bland and Altman, 2003). The predicted quantitative measures were derived by first determining the linear best-fit regression equation between the original qualitative measures and orginal quantitative measures, then applying the original qualitative measrues to the regression equation to calculate the predicted quantitative measures. As *a priori*, the two methods were deemed to be in agreement if the 95% limits of prediction were within ±3 percent of the predicted trend line. [The author is aware that in general Bland-Altman plots are preferred over regression analysis, however Bland-Altman (Bland and Altman, 2003) themselves indicate that the above regression is preferred when the two methods of measurement have different units]. In addition, box and whiskers plots were produced for the quantitative results at each of the qualitative scores (scale 0 to 3) in order to explore the extent to which the former differed at of the qualitative scores. Pre- to post-intervention changes were assessed for parametric data using a paired samples t-test and non-parametric using a Wilcoxon-Signed rank test. A p-value of < 0.05 was adopted for statistical significance in both the t-test and the Spearman rank-order correlation. Intra-class correlation coefficients were used to examine test-retest (ICC [3, 1]) reliability of the qualitative visual analysis. The ICC classifications of Fleiss (Fleiss, 1986) were used to describe the range of ICC values where less than 0.4 was poor, between 0.4 and 0.75 was fair to good, and greater than 0.75 was excellent. All statistical analyses were performed using IBM SPSS (version 21; IBM, New York, NY, USA).

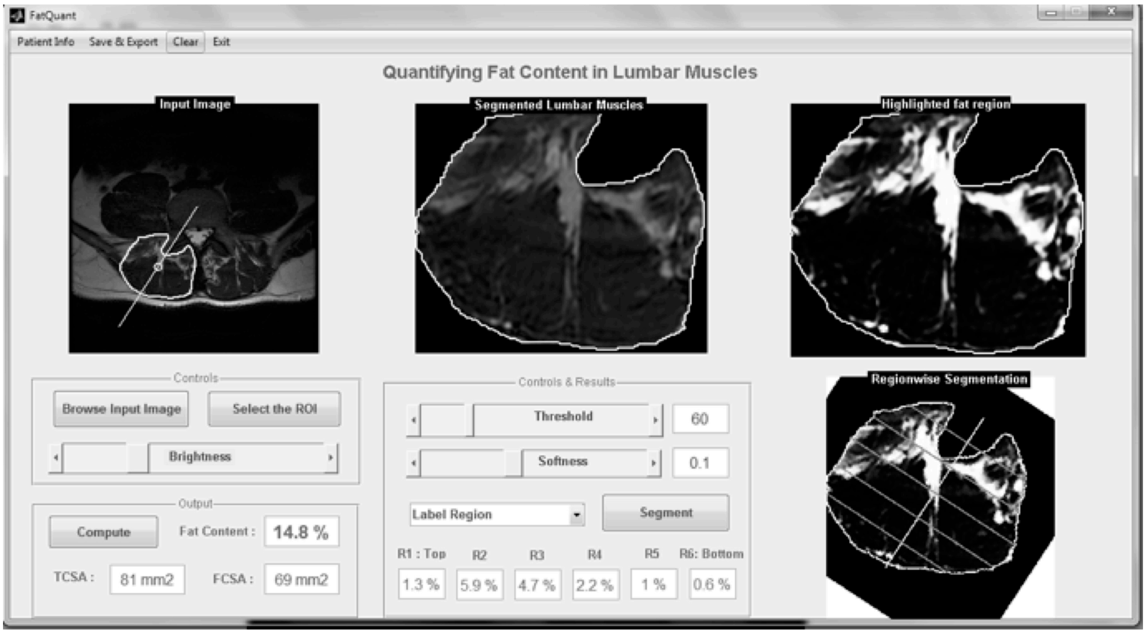

Figure 25: Screenshot of the Graphical User Interface used to calculate fat infiltration

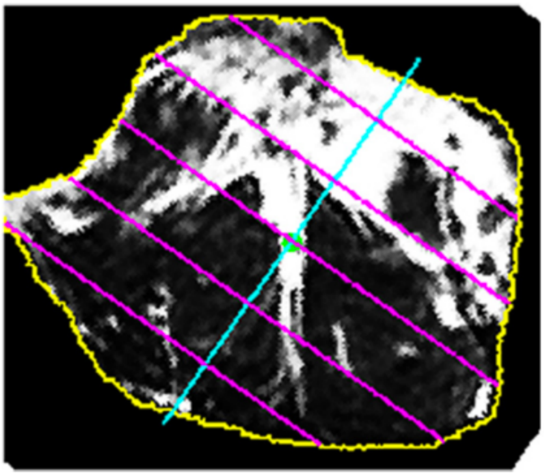

Figure 26: Defining of sub-regions based on distance from the centre of the vertebral body.

14.1.3 Results

Results of the t-test highlighted significant reductions in the percentage of lumbar paraspinal fat infiltration in the quantitative computer based analysis on both right and left sides at L3L4 and at L4L5 levels from pre- to post-intervention (Table 49). No significant changes were observed at the L5S1 level. Results from the Wilcoxon Signed Rank test demonstrated no significant between-group difference in lumbar fat infiltration measured using the visual qualitative analysis (p = 0.26 to 0.47) (Table 50). The ICC was calculated at 0.97 giving an excellent level of intra-rater reliability (Fleiss, 1986), similar values have been seen elsewhere in the literature (Willemink *et al.*, 2012). Some fluctuations were observed in the percentage group distributions for fat infiltration between pre- and post- measurements from the visual grading (Table 51). The regression of the predicted quantitative measures on to the actual quantitative measures show that the interval of the 95% prediction limits are 20.2 percent, 10.1 on either side of the prediction (Figure 27). This is far in excess of the a prioir set limit of agreement of ±3 percent. Figure 28 shows the box and whisker plots for the quantitative results at each of the qualitative scores (scale 0 to 3). They indicate that there is notable overlap between the quantitative measures at the corresponding qualitative scores (sacle 0 to 3), especially for qualitative scores 0 and 1.

Table 49: Percentage fat infiltration of the lumbar paraspinal muscles

L3L4	**Left pre-**	**Left post-**		**Right pre-**	**Right post-**	
	Mean	**Mean**	**Change**	**Mean**	**Mean**	**Change**
Total	13.0 ± 8.2[2]	10.0 ± 6.3	-23%	12.1 ± 6.1[2]	9.4 ± 5.3	-22%
R1	2.8 ± 1.1[2]	2.1 ± 1.2	-23%	2.6 ± 0.9[2]	2.2 ± 1.2	-16%
R2	2.8 ± 2.1[2]	2.3 ± 2.1	-19%	2.3 ± 1.6[2]	1.8 ± 1.3	-22%
R3	2.3 ± 2.2[2]	1.7 ± 1.4	-28%	2.2 ± 1.7[2]	1.7 ± 1.3	-22%
R4	1.7 ± 1.6[2]	1.2 ± 0.9	-29%	1.8 ± 1.5[2]	1.3 ± 0.9	-25%
R5	2.1 ± 1.3[2]	1.6 ± 1.1	-24%	2.1 ± 1.3[2]	1.5 ± 1.0	-29%
R6	1.7 ± 1.1	1.4 ± 1.1	-15%	1.6 ± 1.0[2]	1.2 ± 1.0	-22%

L4L5	**Left pre-**	**Left post-**		**Right pre-**	**Right post-**	
	Mean	**Mean**	**Change**	**Mean**	**Mean**	**Change**
Total	14.3 ± 7.0[2]	11.8 ± 6.0	-18%	13.6 ± 5.6[2]	11.7 ± 5.6	-14%
R1	3.3 ± 1.2	2.8 ± 1.4	-14%	3.0 ± 1.0	3.2 ± 1.4	+6%
R2	4.1 ± 2.2	3.7 ± 2.3	-10%	3.6 ± 1.9[2]	3.1 ± 2.0	-15%
R3	2.6 ±1.5[2]	2.0 ± 1.6	-21%	2.6 ± 1.9[2]	2.2 ± 1.8	-17%
R4	1.7 ± 1.3[2]	1.4 ± 1.1	-19%	1.9 ± 1.6[2]	1.5 ± 1.3	-19%
R5	1.6 ± 1.2[2]	1.1 ± 0.8	-32%	1.6 ± 1.1[2]	1.1 ± 0.7	-31%

R6	1.7 ± 1.0[2]	1.2 ± 0.8	-27%	1.8 ± 1.1[2]	1.3 ± 0.8	-25%

L5S1	**Left pre-**	**Left post-**		**Right pre-**	**Right post-**	
	Mean	**Mean**	**Change**	**Mean**	**Mean**	**Change**
Total	18.0 ± 5.9	17.3 ± 7.0	-3%	17.8 ± 6.2	16.3 ± 7.2	-8%
R1	4.1 ± 1.6	3.9 ± 1.7	-5%	4.1 ± 1.3	3.9 ± 1.4	-4%
R2	6.3 ± 2.0	6.1 ± 2.4	-3%	5.4 ± 2.1	5.3 ± 2.6	-2%
R3	4.2 ± 2.3	4.1 ± 2.3	-3%	4.2 ± 2.2	3.7 ± 2.5	-12%
R4	2.4 ± 1.6	2.2 ± 1.5	-10%	2.5 ± 1.5	2.0 ± 1.8	-20%
R5	1.2 ± 0.8	1.3 ± 1.2	+7%	1.5 ± 0.9[2]	1.2 ± 1.1	-22%
R6	1.4 ± 0.9	1.3 ± 1.3	-8%	1.4 ± 0.8	1.3 ± 1.2	+6%

[2] Significant difference ($p \leq 0.05$) between pre- and post-intervention. R1-R6 are the regions away from the centre of the spinal cord where region 1 is closest and region 6 furthest.

Table 50: Results from the Wilcoxon Signed Rank test comparing differences between qualitative visual analysis pre- and post-intervention

Lumbar level	**z-score**	**p-value**	**Number of ties**	**Number that increased fat**	**Number th reduced fa**
L4L4	-0.78	0.44	35	6	9
L4L5	1.07	0.26	36	9	5
L5S1	0.73	0.47	36	8	6

Table 51: The group distributions for degree of fat infiltration pre- and post-intervention

Lumbar Level	**Number of scans in grading (% of scans in this grading)**			
	0 - No intramuscular fat	**1 – Some fatty streaks**	**2- Less fat than muscle**	**3 – Equal fat and muscle**
L3L4 Pre-	12 (24%)	30 (60%)	6 (12%)	2 (4%)
L3L4 Post-	13 (26%)	31 (62%)	4 (8%)	2 (4%)
L4L5 Pre-	9 (18%)	29 (58%)	10 (20%)	2 (4%)
L4L5 Post-	5 (10%)	33 (66%)	10 (12%)	2 (4%)

L5S1 Pre-	11 (22%)	20 (40%)	17 (34%)	2 (4%)
L5S1 Post-	10 (20%)	22 (44%)	13 (26%)	5 (10%)

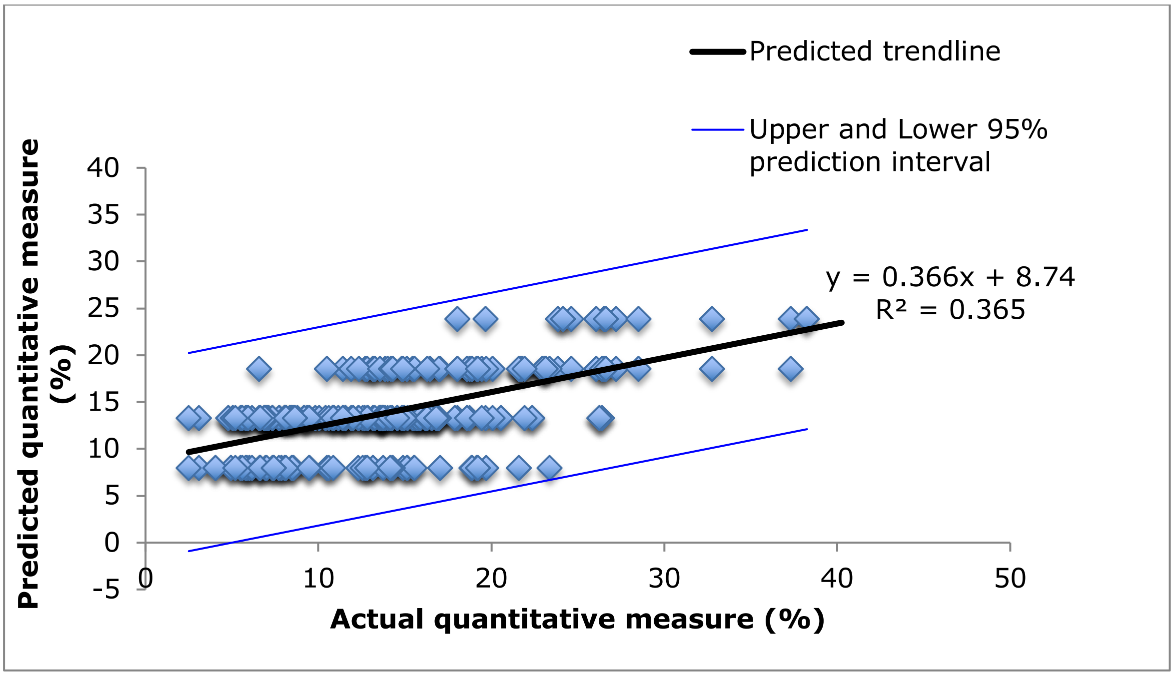

Figure 27: Regression of predicted quantitative measure onto actual quantitative measure (with 95% prediction intervals)

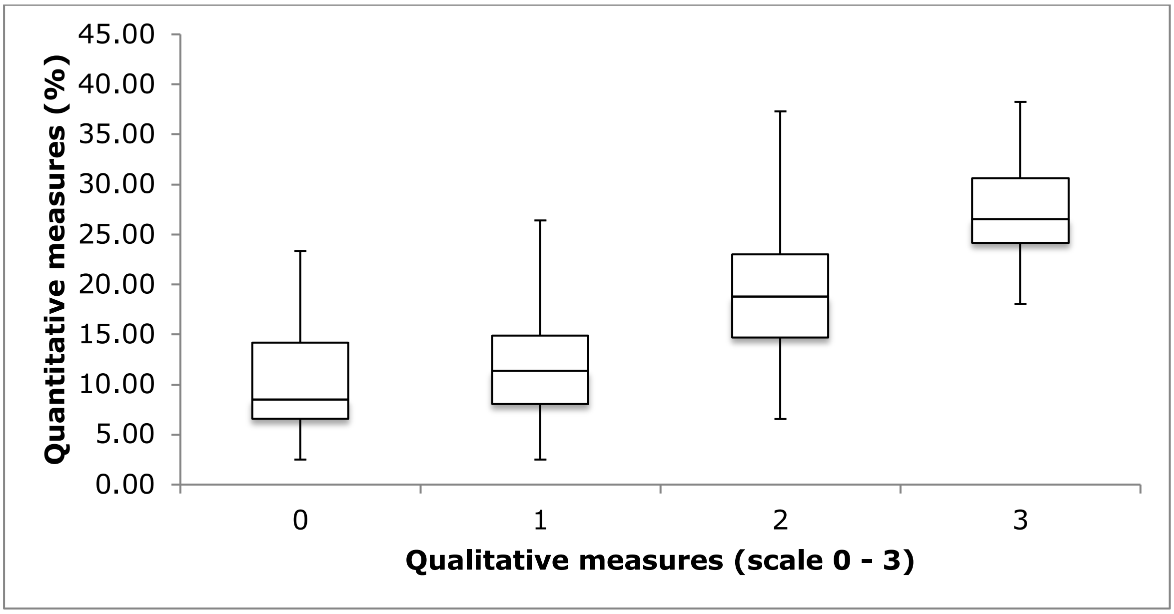

Figure 28: Box plots of quantitative measures for each qualitative measure

14.1.4 Discussion

The results of the current study show a low level of agreement between the two methods of analysis. A significant difference in the ability to detect change in fat infiltration from pre- to post- a resistance training rehabilitation intervention was also seen between the two techniques.

Significant reductions in the percentage of lumbar fat infiltration were observed using the quantitative computer based analysis at the L3L4 and L4L5 lumbar levels (15% to 32%) (Table 49). Furthermore, significant reductions in the majority (20 out of 24) of the sub-regions at the L3L4 and L5S1 levels were observed. No significant change was detected at the L5S1 level with only one sub-region out of twelve demonstrating significant reduction in fat infiltration. In contrast, the qualitative visual analysis techniques demonstrated no significant difference between pre- and post-intervention fat infiltration measurements at any levels. One explanation for this is that the categories used within the qualitative visual analysis were too broad for a change in category to occur given the magnitude of change in lumbar paraspinal fat infiltration observed. Overall, the mean observed change detected using the quantitative computer based analysis was 16%. It is possible that visually, these changes were not enough to necessitate a change in category from, for example, category 2 (less fat than muscle) to category 1 (some fatty streaks). The use of a greater number of categories to determine whether or not a significant change is detectable through qualitative visual analysis could be considered. However, it may be more efficacious to utilise quantitative computer based analysis given the ability to count individual pixels in a region of interest which makes it a very sensitive measure.

The regression of the predicted quantitative measures on to the actual quantitative measures, along with the 95% prediction limits, indicates the agreement between the qualitative and the quantitative measures is not high. Visually, the agreement appears greater when the amount of fat infiltration is very high and very low. Given that the development of low back pain has been associated with a greater deconditioning of the lumbar musculature, which includes greater levels of lumbar fat infiltration (Steele, Bruce-Low and Smith, 2014a), having two methods of analysis that deviate from each other is not ideal. The quantitative computer based system is sensitive to change in a way that qualitative visual analysis is not. For this reason, quantitative computer based analysis techniques could be suggested as being more useful in measuring change in lumbar fat infiltration across an intervention and for more sensitive data analysis in research.

Only one other study to date has attempted to measure change in lumbar paraspinal fat infiltration following an intervention (Willemink *et al.*, 2012). A quantitative computer based system was used to measure total and functional cross-sectional areas and area of fatty infiltration. While the changes observed were not significant, it was possible, as in the current study, to report exact changes in area of fat infiltration. The greater changes in lumbar fat infiltration observed in the current study likely reflect the greater physiological changes due to the higher frequency and volume of training in the current intervention, rather than methodological issues involving the measurement of lumbar paraspinal fat infiltration.

14.1.5 Conclusion

Both quantitative computer based and qualitative visual based analysis of lumbar paraspinal fat infiltration have been used in the literature. The current study demonstrates that there is an unacceptably low level of agreement between the analysis techniques for measuring lumbar paraspinal fat infiltration at a single time point. The level of agreement is least as the lower and higher levels of percentage fat infiltration. In addition, when measuring change following an intervention in lumbar paraspinal fat infiltration, quantitative computer based analysis appears more sensitive to detecting change and should therefore be considered ahead of qualitative visual analysis.

14.2 Appendix 2: Athletic groin pain rehabilitation intervention

Rehabilitation Intervention

Each rehabilitation session was approximately 1 hour in length and took place with a physiotherapist every 12-16 days depending on subject availability. Two physiotherapists undertook all physical assessments and exercise prescription and reviewed their practice together every two months to ensure continuity between them. The first rehabilitation session started on the same day as the initial diagnostic assessment.

Exercise Selection

Level 1

The subjects were taken through each of the level 1 rehabilitation exercise streams (Table 52 and Table 53) with the difficulty of the exercise selected progressed or regressed depending on the subjects ability to execute with appropriate technique (good form and no reproduction of symptoms). Exercises focused not only on segmental control between 2 segments across one joint (i.e. hip flexor, abdominal, lateral control) but also multi-segmental co-ordination through squat, lunge and deadlift. Where a weight was included (i.e. deadlift) the weight selected was modified to allow the subject reach the appropriate number of repetitions and progressed as strength improved. The equipment required was a squat rack, a high and low box or chair and cones. The importance of correct technique was repeatedly emphasised. Level 1 exercises were included throughout the duration of the rehabilitation program with those streams that the athlete displayed full competency on being maintained in 1 session per week.

Table 52: Level 1 Exercise streams and reason for inclusion

Segment	Plane	Stream	Reasons for inclusion
Pelvis on Femur	Sagital	Hip Flexor	Stabiliser of anterior hip and key function in swing leg recovery during running and cutting(45)
Pelvis on Femur	Frontal	Lateral Hip Control	Improves femoracetabular dynamic control to minimise dynamic impingement(59)
Pelvis on Femur	Frontal/Transverse	Lateral Hip Strength	Improves hip abduction and external rotation strength(60)
Thorax on Pelvis; Pelvis on Femur	Sagital/Frontal/Transverse	Abdominal	Improves oblique abdominal strength minimising excessive trunk rotation and pevlic tilt(60)
Multisegmental	Sagital	Double Leg Squat	Improves hip & lumbopelvic strength and control, minimising dynamic impingement(47)
Multisegmental	Sagital	Deadlift	Improves lumbopelvic control and posterior chain strength
Multisegmental	Sagital	Lunge	Improves lumbopelvic control, quadriceps and hip strength
Multisegmental	Sagital/Frontal	Plyometric	Improves rate of force development and single leg reactive strength(61)

Table 53: Level 1 streams and progressions

Stream	Progressions		
Hip Flexor	Supine	Standing Supported	Free standing
Lateral Hip Control	Supported Hip Hitch	Free Standing Hip Hitch	Step Up
Abdominal	Crook Lying Leg Lift	Crook Lying Alternate Leg Drop	Pallof Kneeling Split Lunge
Double Leg Squat	High Goblet Squat	Low Goblet Squat	Front Squat
Lateral Hip Strength	Abduction/External rotation in mini squat	Abduction/External rotation in mini squat at wall	Banded Squat
Deadlift	Hip Hinge	½ Rack Deadlift	Floor Deadlift
Lunge	Split Lunge	Overhead Split Lunge	Weighted Split Lunge
Plyometric	On Spot Hopping	Line Hopping	Cone Hopping

Level 2

These sessions commenced with linear running drills focusing on lumbopelvic control and posture, swing leg recovery and increased rate of force development (Table 54 and Table 55). Once they had completed the drills they carried out the Linear A running program (Table 56) which was designed to complement the running drills while assessing the subjects' running load tolerance and suitability for progression. It started with low volume and low intensity, both of which increased at different points through the program. If a subject had any increase in symptoms the morning after a running session, they were instructed to repeat the same running session when scheduled until they could tolerate it and then progress to the next session.

Linear Drills	Reason for Inclusion
Marching/Skipping	Focus on maintaining neutral lumbopelvic position and trunk posture while maximising vertical ground reaction force production
Barbell/Overhead Running	Focus on maintaining neutral lumbopelvic position and minimising over-stride and excessive trunk rotation
Leg Change Drill	Focus on stance leg stiffness and swing leg recovery

Table 54: Linear running drills and reason for inclusion

Table 55: Linear running drills instruction

Linear	Instructions
Marching/Skipping	March/Skip on the spot with arms locked overhead, maintaining lumbopelvic neutral and with aggressive ground contact
Barbell/Ovehead Running	Run with dowel overhead or barbell across shoulders focusing on tall running posture and keeping stick still
Leg Change Drill	in single leg stand focus on rapid leg change to drive alternating leg extension and swing leg recovery
Complete 5-6 reps of 3-4 sets	
Focus is entirely on quality of exercise execution	

Table 56: Linear A running program

Linear A						
Session	**Distance (meteres)**	**Intensity**	**Recovery**	**Reps**	**Distance**	**Total Distance**
1	400	50%	1 min	6	2400	2400
2	400	50%	1 min	8	3200	3200
3	400	50%	1 min	10	4000	4000
4	400	70%	1 min	10	4000	4000
5	400	85%	1 min	10	4000	4000
6	400	100%	1 min	10	4000	4000
100% intensity was the subjects self rated assessment of maximum effort at that distance						
Subjects progressed to the next level of running if no increase in groin symptoms the next morning						

Level 3

In Level 3, the linear running was progressed to Linear B running program (Table 57) which saw a reduction in volume but increase in intensity starting first from a rolling start but then progressing to a standing start. The linear running drills were maintained as a warm up to this session and were accompanied by multidirectional drills. The focus of the multidirectional drills was to improve segmental control, lateral rate of force development and improve agility prior to returning to sports specific movement (Table 58 and Table 59). They were executed at as high an intensity as possible without reproduction of symptoms. If a subject had any increase in symptoms the morning after a Level 3 session, they were instructed to repeat the same session at the same intensity when scheduled until they could tolerate it and then progress to the next session.

Table 57: Linear B running program

Linear B							
Session	**Distance**	**Intensity**	**Recovery**	**Reps**	**Distance**	**Total Distance**	**Starting Speed**
Warm Up	400	70%	1 min	4	1600	1600	
1	100	70%	30 sec	10	1000	2600	Rolling start x 10m
2	100	85%	30 sec	10	1000	2600	Rolling start x 10m
3	100	100%	30 sec	10	1000	2600	Rolling start x 10m
4	100	100%	30 sec	5	500	2350	Rolling start x 10m
	50	70%	30 sec	5	250		Standing start
5	100	100%	30 sec	5	500	2350	Rolling start x 10m
	50	85%	30 sec	5	500		Standing start
6	100	100%	30 sec	5	500	2350	Rolling start x 10m
	50	100%	30 sec	5	250		Standing start
7	100	100%	30 sec	5	500	2600	Rolling start x 10m
	50	100%	30 sec	10	500		Standing start
Warm up was completed prior to commencing each session warm up and to re-establish good running pattern							
100% intensity was the subjects self rated assessment of maximum effort at that distance							
Subjects progressed to the next level of running if no increase in groin symptoms the next morning							

Table 58: Multidirectional running drills and reason for inclusion

Multidirectional Drills	Reason for Inclusion
Lateral Shuffle	To optimise frontal plane rate of force development and minimise loss of segmental control between the trunk and pelvis
Zig Zag Running	To optimise trunk and hip control and foot placement during side step
180 Degree Cone Cutting	To optimise rate of force development and push off during cutting

Table 59: Multidirectional running drills

Multidirectional	Instructions
Lateral Shuffle	Side Shuffle between 2 cones 8 metres apart with arms locked overhead focusing on getting away from the cones as quickly as possible. Progressed to react to instruction or to shadow opponent while shuffling
Zig Zag Cutting	5 cones in zig zag formation, 5 metres apart from each other. Run and cut as quickly as possible around the cones. Add holding a med ball for increase resistance and higher centre of mass
180 Degree Cone cutting	5 cones in a semi circle, start in the middle and run at any cone and cut back straight to the starting point.Add holding a med ball for increase resistance and higher centre of mass
Start at 50% intensity and increase between sessions as long as symptom free during drill	
Focus is entirely on quality of exercise execution	
3-4 sets of 5-6 reps	

Progression Criteria

Progression from level 1 to level 2 was indicated once the subject had a negative crossover sign (Thorborg, Bandholm and Hölmich, 2013) which was usually achieved by the second session. Progression from level 2 to level 3 was indicated once the subject had symmetrical internal hip rotation at 90°, pain-free squeeze at 45° and symptom free completion of the Linear A running program.

Progression from level 3 to repeat 3D testing and return to play was symptom free completion of the Linear B running program and symptom free completion of the multidirectional drills at maximum intensity.

Any subject who did not meet the criteria to progress to the next level at their review appointment went back through each of the components of that level of the rehabilitation program and a rehab tracker, which they filled out between appointments charting progress, to identify any potential barriers to progression at the next review appointment.

Dosage

The subjects were instructed to complete 3-4 sets of 6-8 reps of each exercise in Level 1 four times per week (i.e. two days on, 1 day off) at their own training base.

The level 2 linear running sessions were also introduced 3 times per week, with at least one day rest in between sessions. They could be done on the same day or another day as a Level 1 session as best suited the subjects schedule. On days when both sessions were done on the same day, the level 1 session was to be completed first. The linear drills were carried out for 5-6 reps and 3-4 sets with a high emphasis on quality and intensity prior to commencing linear running program A.

The level 3 sessions followed the same schedule as level 2 (3 times per week with 1 day rest in between). The multidirectional drills were carried out for 5-6 reps and 3-4 sets with a high emphasis on quality and intensity and were preceded by the linear drills and followed by the Linear B running program.

Program compliance

Each subject was given a printed handout of all the exercises and main cues for each, in addition to each exercise being captured on video using Dartfish™

software for all exercises and levels of the program and the videos hosted online for the subject to review between sessions. Subjects completed a “rehab tracker” between review sessions which noted compliance as well as any issues with any of the exercises which could be assessed at the next review. Subjects were advised that should any exercise reproduce their groin symptoms, they should review their videos and amend their technique to resolve and if unable to do so these exercises should be discontinued and their assigned physiotherapist contacted.