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Low Cost Angular Displacement Sensors for Biomechanical Applications - A Review

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Abstract In the general scientific quest for increased quality of life a natural ambition is to know more about human body kinematics. Varied knowledge can be extracted from sensors placed on human body and through associated biomechanical parameter evaluation the causal connection between different biomechanical parameters and medical conditions can be inferred. From a biomechanical point of view, one of the most important parameters within the human body is the amplitude of angular movements of joints. Although many angular sensors are used in industry, particular characteristics such as small size, flexibility and appropriate attachment methods must be taken into consideration when estimating the amplitude of movement of human joints. This paper reviews the existing low cost easy to manipulate angular sensors listed in the scientific literature, which currently are or could be used in rehabilitation engineering, physiotherapy or biomechanical evaluations in sport. The review is carried out in terms of a classification based on the sensors' working principles and includes resistive, capacitive, magnetic and piezoresistive sensors.

Keywords: *low cost sensor, bend sensor, flexible sensor, angular displacement sensor, resistive sensor*

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1. Introduction

In the past decade demands have risen for small, flexible sensors and actuators in many different fields including robotics, toys, medical equipment and instrumentation, rehabilitation, sport applications, automotive industry etc. In applications that require instrumenting a human, such as in sport or medical applications, conventional bend sensors are unacceptably rigid and inconvenient to use. Although alternatives are emerging, to the best of our knowledge, there is no comprehensive review of bending sensors specifically tailored to these kinds of applications. The focus is on low cost sensors which could be widely used in rehabilitation and everyday life applications. The aim of this paper is to provide such a review, focusing on both commercially available and laboratory-made bending sensors.

The review is also motivated by the authors' interests in next generation rehabilitation equipment and monitoring systems for physiotherapeutic exercises and sport biomechanics. Since these systems are in direct contact with the human body, structural flexibility, small size and appropriate means of attachment are essential considerations. Another important consideration is that in biomechanical systems, the instantaneous axis of rotation is not very well defined or can move during rotation, which can make angular displacement measurements an arduous process.

The present article's aim is to review the scientific literature concerning the operating principles, applications and the use of flexible angular sensors, providing a comprehensive study about the design of such sensors, their limitations and their potential applications. We use the term flexible angular sensor to mean a sensor in a flexible structure, or composed from small rigid sensor elements without rigid physical connection, which can measure angular stimulus.

This brief introduction is followed by the description of the review methodology emphasizing the databases and searching criteria employed. After a short classification of the sensors regarding their working principle, we proceed to describe each sensor group considered. The penultimate part of the paper details some sensors which could not be included in any of the enumerated classes, but that can be used in the considered applications. The last section concludes the work and gives indications about the future use of these sensors.

2. Methods

The literature review and scientific article selection was made in as comprehensive a manner as possible. A protocol which has subjective and objective features,

inclusion/ exclusion criteria was specified. The considered articles are English language, peer-review articles or patents. Review articles are considered as a special type of articles, wherefrom general information or references were extracted for further processing.

The literature research was made online, based on several online scientific bibliographic databases from June 2012 till January 2013, as listed in Table 1. The first inclusion/ exclusion criterion was regarding the title of the study while the second regarded the content of its abstract. A scientific article was further considered, if it passed the previous filtering phase. Finally, after their meticulous examination, the articles found to be irrelevant or with poor data and/ or description were excluded, however in this last phase the references of the articles were checked over and considered for review.

Sensors in each category are reviewed in chronological order starting with first sensors which emerged in the specific field to the sensors of our days.

Table 1. Scientific Databases Used in The Present Review

Name of database	Abbreviation	Web page (www.)
Scopus	Scopus	scopus.com
Science Direct	Science Direct	sciencedirect.com
SpringerLink	SpringerLink	springerlink.com
Wiley Online Library	Wiley	onlinelibrary.wiley.com
IEEE/IET Electronic Library	IEEE Xplore	ieeexplore.ieee.org
IOP Science	IoP	iopscience.iop.org
Optics InfoBase	Optics Letters	opticsinfobase.org
Multidisciplinary Digital Publishing Institute	MDPI	mdpi.com
Web of Knowledge	ISI	webofknowledge.com

3. Classification of Angular Displacement Sensors

At the very beginning of the exploration, the authors carried out a search using general terms describing the targeted sensors, as for example: bend sensor, flexible sensor, curvature sensor, tilt sensor, angular bend sensor, and angular displacement sensor. From the output of the search, the most important types of sensors emerged, but a more specific research was needed to investigate the different sensors for each class, to find the most prominent studies of the field. Following a brief literature review the most valuable classification was found to be based on the sensor's working principle. We thus classify sensors into four groups: resistive, capacitive, magnetic and piezoresistive. For general use the resistive sensors are the most widespread ones, with several commercially available products.

The rest of the document will report each of the sensor groups, describing their use and particularities as found in the scientific literature. In the last section conclusions will be drawn about the sensors characteristics and applications are to be suggested.

4. Sensors

4.1. Resistive Sensors

Most of the commercially available bend sensors are resistive. They are small, light, and have a reduced fabrication cost, which are the advantages that make them employable in many different applications. Most of these sensors can be used in dusty, dirty environments and are not affected by liquids or humidity [1]. Their most important characteristics are the low cost, reliability and ease of use.

The summary of the literature review of resistive bending sensors that was made in the online databases is listed in Table 2. Some additional articles were found by searching other terms or references of the found articles.

The first resistive sensors were very simple and relied on basic mathematical principles. In [2] a flexible angular sensor based on radial circumference difference of circles is described. Two equal length, inelastic wires positioned at a constant distance are bent in the plane they define. At one end the wires are bonded together while at the other ends they are attached to the cursor of two potentiometers. From the difference in resistance measured by the Wheatstone bridge, the angular variation of the monitored joint can be determined. Due to the Wheatstone bridge, the sensor is almost temperature independent; however hysteresis occurs if the bend exceeds 50°.

Another article explores a similar mathematical principle based on human skin elongation near an anatomical joint. During the flexion of a limb, the skin around the joint stretches, as does the surrounding clothing. According to [3], the skin around the knee stretches lengthwise about 40% of its normal length requiring 25-30% stretchability from the fabric to ensure general comfort. Motivated by this principle, a resistive bending sensor based upon the elongation of the fabric is presented in [4]. The reported technique permits continuous, long-term monitoring of a human joint, based on the stretch of the skin and the elastic fabric. A conductive fiber is attached at one end (end 'a') to the fabric, while the other end (end 'b') is coupled to an elastic cord. At an appropriate distance from the coupled end ('b' end), a wire contact is permanently stitched into the clothing. During bending, the conductive fiber will slide beside the wire contact, resulting in increase of the wire length between the two terminals leading to an increase in resistance.

The articles [2,4] are based on different principles, with the similitude that both of them are build up on long metallic wires. The authors of this review would recommend these sensors for movements of big amplitude, around longer body segment's articulations as for example knee, elbow. These sensors would be less accurate to use around small body segment's articulations as fingers, wrist or spinal regions.

These days, resistive sensors are often based on the piezoresistive effect. According to this a resistive sensor's electrical resistance change when it is deformed [5]. The distortion modulates the geometry of the sensor and its specific resistivity [6]. The resistance variation due to geometrical changes can be described by the equation (1), where ρ is electrical resistivity of a material; L is the

length of the conductor; S is the cross section area of the conductor. The ratio l/S is called geometry factor.

$$R = \frac{\rho \cdot l}{S} \quad (1)$$

Table 2. Search Result for The Resistive Group

Search Fields	Keyword	Database	Found	Title	Abstract	Reading
Topic	resistive bend sensor	Web of Knowledge	36	5	3	1
Title-abs-key	resistive bend sensor	Scopus	21	4	2	2
-	resistive "bend sensor"	SpringerLink	6	3	1	1
ALL	resistive "bend sensor"	Wiley – Online Library	12	0	0	0
Metadata Only	resistive bend sensor	IEEE	20	5	3	0
Keywords	wearable	MDPI	40	5	0	0

By bending the substrate to which a sensor is attached, a variation in length and cross-section of the sensitive material can be observed. With the increase of the bending angle the length of the sensing material increases and its cross section decreases. Both of the two variations increase resistance, resulting in an accentuated increase of the sensor resistance.

The piezoresistive effect has been broadly exploited in the scientific literature. Not surprisingly many patents have been built on the piezoresistive effect as pressure, force or even bending sensors. In [7] different materials, technologies, and embodiments suitable for resistive bend sensors are discussed. Materials can be conductive elastomers, conductive inks, and conductive fluids.

A conductive elastomer is a rubber-like material, impregnated with conductive fibers or particles (metallic or carbon), which conforms to an eq. 1-like formula. Usually a conductive elastomer is bonded or deposited to the substrate that is attached to the structure to be monitored. When this structure bends, the flexible substrate follows its shape and stretches the elastomer. A similar sensor can be obtained with a conductive fluid (electrolytic solutions or conductive oil) embodied in an elastic tube.

In the case of the conductive ink, which comprise carbon particle in a binder, the bending of the substrate can generate two different behaviors within the ink. In the first type of ink the stretch increases the distance between the carbon particles, resulting in a slight resistance increase. In the other type of ink, the consequence of stretching is the formation of the so-called micro cracks, perpendicular to the length of the sensor, resulting in a dramatic increase in resistance. While without micro cracks the sensor presents better durability to the detriment of lower resolution, with micro cracks the sensor sensitivity increases at the cost of lower durability. Usually different inks are mixed to produce a sensor with required characteristics and a customized ink generally presents both behaviors during bending.

While the resistance of conductive inks is relatively high, metallic conductive materials are deposited on the substrate in a certain pattern in order to reduce its general resistance. This technique can be used for dedicated sensor designs, which are more sensitive in some areas and less in others.

The most known commercially available resistive sensors are Bi-Flex Sensors™ from *Image Scientific Instruments*, Bend Sensors® from *Flexpoint*, Flexiforce Sensors from Tekscan Inc., Abrams Gentile sensor and Spectra Symbol. Among them, the most studied and used are the Flexpoint and the Image SI sensors. The Flexpoint sensor is a conductive ink-based sensor, changing its resistance up to a factor of ten at full flexion [8]. These sensors have a standardized connector, for easy incorporation of the sensors in different circuitries, and can be purchased in different lengths starting from 1 inch. The sensor behavior is tested and presented in detail in [9].

One of the first biomechanical applications of the Flexpoint sensor is a data glove [10,11]. In [10] the authors present two modifications in order to enhance stability and linearity. The first modification consists of gluing a thin polyvinyl film over the carbon layer, while the second is placement of a resistance in parallel during data acquisition. In repeatability and reliability experiments, the proposed glove presents an intraclass correlation coefficient (ICC) of 0.93 and a mean SD of 1.59°.

The work reported in [12] compares the Flexpoint's Bend Sensor and Image SI's Bi-Flex Sensors linearity. Despite its nonlinear behavior, the Image SI sensor, presents better sensibility [9,12]. In [13] the same authors propose another possibility regarding the linearization of the Flexpoint sensors. Their idea was to change the sensing element initial rectangular geometry, by cutting it to a certain pattern. The experiments showed a significant linearization of the sensor characteristic function. In another article the static and dynamic evaluation of these sensors is performed and an RLC circuit is proposed to model its behavior [14].

A different category of applications of the resistive bend sensors are in the field of robotics, power-assisting devices and medical microsystems. A McKibben pneumatic actuator, [15] is used in many robotics related applications such as an artificial muscle, with high force-weight ratio. During its lengthening estimation, mostly rigid sensors were used as linear potentiometers/ encoders, however their attachment to the flexible structure is cumbersome. In order to overcome this shortcoming, a flexible electro-conductive sensor is presented in [16] to measure the artificial muscle circumference variation, in order to estimate its axial shift. The electro-conductive rubber sensor from the Exseal Corporation is wound around the pneumatic sensor while two conductive wires are inserted in the sensor. The elongation can be estimated hence the deformation between these two points is reflected by the change in resistance of the sensor.

The sensors presented in the last mentioned articles are commercially available sensors readily adapted for different applications. As the test made by several scientific groups and the authors of this review, showed, these sensors are designed for articulations of short segments and medium angle measurements. After a certain value of bending, the sensors show high hysteresis and make their use cumbersome.

As presented in the cited articles, the commercially available sensors are not adequate for many biomechanical applications. They do not exhibit the

required reliability and especially repeatability in use. As a result, many scientific articles still consider the development of resistive sensors in their work. In [17] Cochrane et al. developed a resistive sensor for measuring the deformations within a textile. For the sensitive material a thermoplastic polymer and carbon black powder are used in different proportions. The scientific group performed a comparison between different fabrication techniques, where a solvent mixing medium (chloroform) emerged as the best performer. The reported sensor has the advantages of compatible mechanical properties with textiles, property which permits the continuous and unaffected movement of the textile. The main environmental propriety affecting the sensor was found to be humidity. The absorption into a nylon fabric is insignificant as it can be seen in a later article [18]. The use of the developed 2.5 mm x 10 mm sensor was reported in the context of determining deformation in a parachute canopy. As tests showed, this type of sensors can be used to measure small stretches and implicitly small angular variations. It is especially suitable for sensorized garments which not only bends with the human body, but stretches as well.

While the scientific literature does not reveal one over-arching research direction for resistive sensors in the following we present other approaches which may be considered in the future as new resistive bending sensor constructions. In [19] the authors developed, beside several flexible sensors, a conductive liquid based curvature sensor, suitable for biomechanical applications. The sensor consists of a transparent elastomer film with microchannels filled with conductive liquid, and a sensing element. During bending, the sensing element exerts pressure on the microchannels, deforming its cross section leading to resistance change. The sensor was used for a finger joint evaluation. According to the authors, the sensor construction, microchannels and sensing element position facilitates insensitivity to strain. This sensor would suit for applications where the main purposes of the study are the amplitudes of the movements and the stretch doesn't present interest. The article showed that in biomechanical applications would be suitable for measuring low amplitude movements and articulations with short segments.

Another liquid based sensor is presented in [20] where channels in silicon rubber housing are filled with electro conductive fluid, in order to form a tactile sensor. From the figures presented in the article it is clear that the sensor is sensitive to bending due to its lengthening and cross section decrease. In the experiments, the sensor works up to a 60% stretch of its initial length and it presents high sensitivity. During the study of bending influence on the tactile sensor, the sensor was attached to a curved surface, while static resistive variations were measured within different curvatures. In this construction the influence of bending was not significant. For biomedical applications, the sensor could be used by attaching its ends to different segments of a limb, around the joint.

4.2. Capacitive Sensors

In continuous monitoring mode, resistive methods will consumer power, even if the sensor is in a neutral position. Given their functional characteristics, capacitive sensors can result in lower power consumption. Another advantage of the capacitive sensors is the lack of physical contact between the two conductive surfaces.

The capacitive sensors have an extreme large range of applications. They are used in flow, pressure, liquid level, proximity, thickness measurements or as linear/ angular position and displacement detector. The smallest ones are in the order of micrometers and are able to detect displacements less than a micrometer [21].

In terms of structure, a capacitor consists of an insulator (dielectric) inserted between two conductive plates. They are available in flat (parallel), cylindrical and spherical configurations, but in the sensor industry the most often used sensors are the planar capacitors. Their sensing mechanism consists of plate area, distance between plates, or dielectric variation in correspondence with the analyzed phenomena, while the preferred influenced variable is the distance between the armatures. The operating principle of these sensors is based on the equation (2), where ε_r is the relative electric permeability of the dielectric material between the two electrodes; S is the common area of the plates; d is the distance between plates.

$$C = \frac{\varepsilon_0 \varepsilon_r S}{d} \tag{2}$$

An interesting application of the previously presented phenomena is described in [22]. A glove equipped with a capacitive (and a pneumatic) sensor is used to determine the relative position of the thumb, index finger and palm. The capacitive sensor consists of three electrodes. One of them is located on the index finger while the others on the palm and thumb. From the signal received from index-thumb and index-palm capacitors, the distance and the angle between them can be deduced. The authors did not present the error of the system; however they demonstrate the use of the sensor for gesture recognition.

Plate area variation and distance increase between the electrodes is exploited in patent presented in [23]. A dielectric material is inserted between two comb-patterned metallic layer plates. At one end the two elements are bonded, while at the other end they can slide relatively to each other. The bending angle of the measured structure can be deduced from the relative alignment of the two patterned portions. In the case when the offset of the two sides is zero in initial state, beside the amplitude of the bending, the sensor can distinguish negative and positive angles. The presented sensor, according to the authors, can be used in bending measurement for human fingers or different human body segments; however the authors of this article suppose that the same principle could be used to design longer sensors with bigger distance between the comb-patterns. This later could be used for low amplitude movements' measurements of long segments as the regions of the spine. Sensors based on this patent or based on similar concepts was not found by authors.

A more precise sensor is presented in [24] within a parallel plate capacitor, which can measure the pure bending strain of an element. The bottom plate is fixed to the bending structure and conforms to the structure, while the other remains straight, widening the gap between the plates during the bending. The sensor has a high nominal capacitance, good sensitivity and compact structure. Within a 10 mm length sensor several designs (different metal coverage, areas and gaps between the plates) were

tested. The preferred sensor, with a 3μm gap between two 2x4 mm^2 plates, was used in spinal fusion monitoring. It exhibited high sensitivity especially at the beginning of the bending process. It is suitable for low angular motion detection.

The smallest capacitive sensors are generally used as pressure or force sensors. Dobrynska et al. [25] have developed a flexible force sensor, which changes its capacitance in response to normal force (due to armature approach). A polyimide film was used as flexible support and elastic dielectric layer between the grid-like aluminum electrodes. Even though the article does not deal with sensor behavior under bending, this sensor could be used for bending analysis after a preliminary calibration procedure.

In another article [26] Lee et al. propose a flexible capacitive tactile sensor, which can measure normal and shear force. The polydimethylsiloxane (PDMS) tactile cell incorporates four capacitors. When the cell is compressed the distance between the electrodes alters. Using a differential approach, the force direction can be evaluated. Thus when the force is perpendicular to the cell, the capacitance variation in the different capacitors are proportional; otherwise there is an inverse capacitance variation between two adjacent capacitors. This type of sensor could be used to determine the bending of a structure in different planes, as the trunk monitoring in sagittal and lateral planes, which would have a similar effect on the cells. However for this application the structure must be redesigned.

A new sensor, described by Zhang et al. [27] reports the fabrication, numerical analysis and electromechanical characterization of a flexible capacitor-like, transparent bend sensor. The principle of operation is based on the change of the tunneling current when the porous film is compressed during bending. The sensor is transparent and as such proposed applications include contact lens deformation and surface crack detection. For biomechanical use good attachment procedures need to be conceived.

The last presented sensor, reported by Nishijima et al. [28] is based on an electrostatic motor. It consists of two plastic flexible printed circuit (FPC) sheets, containing three phase electrodes with constant pitch between them. When used to measure bending, the two sheets are bonded at one end, while sliding freely on the other end. To reduce friction, glass beads were dispersed between the two films. The tested 115 mm length sensor could measure bending between -0.66 and +0.66 radians, with a slight hysteresis due to friction.

4.3. Magnetic Sensors

Thanks to the recent advancements in microelectromechanical systems (MEMS) technology, the interest in magnetoelastic sensors has increased. They are applicable in different fields such as stress, displacement or even vibrations sensors. Since 1842, when W. P. Joule first observed the magnetostriction effect [29], other magnetoelasticity phenomena have been discovered such as volume magnetostriction, dipolar magnetostriction (form effect), Delta-E effect, Wiedemann effect and their inverse effects. The magnetostriction effect refers to dimensional alteration of a ferromagnetic material during magnetization, namely, the magnetic energy is converted into mechanical energy. When applying an external stress to the material, magnetization variation can be observed as the magnetic permeability is sensitive to mechanical stress [30]. This latter effect is known in the scientific literature as the Villari effect.

In the field of displacement sensors the exploitation of the Villari effect is the most widespread. In [31] a novel magnetoelastic bilayer sensor is adopted to detect upper femoral musculature contraction during muscle diagnosis by means of electrical stimulation. A magnetostrictive layer is fixed on a counter layer whose task is to shift the neutral surface out of the sensitive layer, producing pure tensile or compressive stress. A pickup coil measures the change of magnetic permeability induced by mechanical stress. In the experiments the sensor signal can be evaluated up to a 300 Hz sample rate. Even if analytical or numerical data analyses are not presented, figures show reliable behavior for a 10 cm long sensor. The presented light-weight sensor is suitable to use in applications where the amplitude of movement is small, however it is not a widespread technique but an individual example.

A more common magnetic sensor is based on the Hall effect. When applying a perpendicular magnetic field to a thin conductive plate carrying current, a small electrical tension can be observed between the sides of the plate. The voltage amplitude observed across the plate is constant and depends on the magnetic field (B), electric current (I), angle between their directions (α), a Hall effect constant (K_H) and the conductor thickness (z) given by the following equation [32]:

$$V_H = \frac{B * K_H * I * \sin\alpha}{z} \quad (3)$$

Under general conditions, the Hall effect is slightly observable in metallic components, however it is an important and pronounced magnetic characteristic of semiconductor materials. Advantages include insensitivity to vibration, humidity, dust and constant characteristics over time, whereas disadvantages include the influence of external magnetic field. A patented data glove named Humanglove [33] uses 20 Hall effect sensors having a 0.4° resolution over a range of 90°, with 1% linearity and about 1° accuracy. From the range of commercially available magnetic sensors base on Hall effect it can be seen, that the Hall effect based sensors would be suitable to use for small angle variations. Nonetheless they need adjacent sensor elements, which makes them cumbersome to attach to joints such as ankle or knee.

4.4. Piezoelectric Sensors

In our study piezoelectric polymeric sensors form a smaller bending sensor category. They convert the input mechanical energy into electrical potential difference between two opposite surfaces, due to the polarization effect [34]. The first commercially available piezoelectric materials were the quartz crystals, but these days the most researched sensors use piezoelectric polymers.

Several scientific groups have made experiments with polyvinylidene fluoride (PVDF) based sensors. A trilayer structure comprising a PVDF layer between two polypyrrol (PPy) layers, forming an electrolyte reservoir, is reported in [35]. The cantilever structure sensor, anchored at one end, produces an output current when

applying a force at the free end. Tests were made applying deformations with different amplitudes and frequencies. Results show a visible peak shift (increase) of the output current with the increase of the input, particularly at low frequencies. The same principle but in different construction can be applied to biomechanical motion monitoring. The force can be applied by the sensors itself and the output would correspond to the magnitude of flexion.

Table 3. Resistive and Capacitive Sensors

Reference/ Year	Application	Algorithm & signal processing	Test length	Gold standard	Used components	Error/ Analysis	Term used
Resistive sensors							
[2], 1998	Knee angle evaluation	Differetial Wheatstone bridge	-	Manual goniometer	Conductive wire	Ea = ±2°, A	flexible angular sensor
[4], 2005	Hip and Knee joint monitoring	Linear regression predictor, quadratic predictor	-	Electrogoniometer , Rotatory goniometer	Silver plated nylon yarn	RMSE =3.5°, N	conductive fibber
[10], 2009	Sensor glove for neurophysiologic assessment	-	40s	Manual goniometer	Flexpoint sensor	SD=1.59°, E	resistive bend sensor
[11], 2007	Instrumented glove	Average	10 min	Manual goniometer	Flexpoint sensor	Er <11°, E	bend sensor
[13], 2011	Data glove	Digital multimeter. No further processing	-	Stepper motor	Flexpoint sensor	-, A	bend sensor
[14], 2010	Motion analysis	-	sec	Stepper motor	Image SI FLX03	-, N	strain sensor
[16], 2009	McKibben pneumatic actuator lengthening	Low-pass filter	<7 min	Potentiometer	Electro conductive rubber	RMSE<0.8m m, N,A	flexible sensor
[17], 2007	Strain determination in textiles	-	-	-	TPE+CB	-, N	flexible strain sensor
[19], 2011	Tested on finger	Flukeview Forms Basic software	≈1 min	Video capture system	Elastomer film + Conductive liquid	Ea ≈20°, -	curvature sensor
Capacitive sensors							
[24], 2007	Spinal fusion monitoring	-	-	-	Cantilever structure	Er = 5%, A, E	Bending strain sensor
[25], 2007	Force sensor for plantar surface	-	-	-	Polymide dielectric, aluminium electrodes	-, E	Flexible force sensor
[26], 2008	Normal & Shear force sensor	Averaging	-	-	PDMS layer embedded electrodes	-, N, E	Tactile sensor
[27], 2009	Crack or deformation detection	Averaging	-	-	Porous film	-, N, E	Bending transducer
[28], 2009	Pilot experiment	Equivalent capacitance network model	-	Capacitive laser displacement sensor	FPC & lubrication film	Er = 10%, A	Flexible sensor

Abbreviations:

RMSE- root mean square error	SD – standard deviation	E - Experimental
Ea – absolute error	TPE - thermoplastic elastomer	A - Analytical
Er – relative error		N - Numerical

Based on another PVDF film sensor, a new method for measuring small deformations or insect locomotion is presented in [36]. At one end the film is fixed while the other end is attached to the moving limb. Under the relative motion of the two ends the initially flat sensor is buckled, providing electrical charge between the two ends. The article presents an analytical model of the sensor that considers hysteresis and is validated with experimental results with different size sensors. Sensor dimensions were from 10x1 mm to 32x3 mm.

5. Conclusions

This paper presents a comprehensive review of the low cost flexible bending sensors currently used, or that could potentially be used in human body motion analysis. The literature review was carried out based on objective and subjective criteria, in the most known and used databases of this field. In the first step, the authors attempted to discover the possible sensors by searching general keywords, but the results were not satisfying. Further investigation was carried out to discover representative flexible bending sensors that are or could be applied in biomechanical applications.

The scientific literature analysis revealed the main differences between the sensors made few decades ago and the current ones. The fundamental differences seem to be the sensor reliability and repeatability of which we can see a significant increase over time.

While the first sensors used in human joint motion amplitude evaluation were the manual goniometers, the resistive sensors were one of the first to be tested for continuous human motion monitoring. In many cases, the goniometer based systems provide acceptable data with low costs, but in the case of a variable center of rotation the use of this instrument is cumbersome. In early deployments, resistive sensors were based on simple mathematic formulae however these days, attention is focused on the exploitation of the characteristics of resistive materials. Even if this sensor group has commercially available products, they are usually not sufficiently precise or lack a proper flexible substrate so the experimentation continues in this area.

A less researched bending sensor category consists of the capacitive sensors. They present low power consumption, while for capacitance determination the electrical tension needs to be applied only for a short time at the capacitance armatures. The most exploited sensors are the parallel plate capacitors, by virtue of their simple construction. The most manipulated parameters are the relative permeability, plate area variation and the distance between the plates. Capacitive bending sensors are not yet commercially available and stop at laboratory level, but their advantage of low power consumption could lead to many applications in different fields of the flexible sensors.

A small number of articles describe the use of magnetic effects, generally the Hall effect, for several sensors. For many years the use of magnetic sensors for biomechanical applications was almost impossible, while with the advancement of the MEMS technology many new sensor constructions and materials are revealed. However, drawbacks such as the influence of different ferromagnetic materials on the sensors can make their use cumbersome.

The literature review indicates an increased interest in electro active polymers (EAP) as piezoresistive, piezoelectric, magnetoresistive EAP. The piezoresistive polymers have been used in garments to measure human body kinematics, or as separate sensors in several industrial applications. In the piezoelectric sensor category the most studied are the PVDF sensors. Their flexibility and functional characteristics are encouraging for use on bodies of variable sizes (both human and animal).

Each section describing different sensor types indicates suitability of their use in different applications. Different construction and sensitivity sensors are required for monitoring motion of joints from specific body parts. While monitoring the movement of the spinal regions implies long, sensitive sensors with angle variation less than 60 degrees, the motions of fingers require short sensors able to sense bending of more than 100 degrees.

To better compare the performance of different types of sensors Table 3 was elaborated. It can be seen from the table that the measurement error does not show significant difference between the sensor types. The error is more dependent on the experiment type and the sensor application procedure. Smaller error is achieved when sensors are attached to experimental apparatus in respect to human body experiments. These differences occur due to the center of rotation variability and additional motion introduced by the skin which skews the measurements of the joint motion, whereas this effect is not present in artificial experimental structures.

A general overview of these sensors brings to the light the necessity of using reference systems for better comparison of experimental results. It is also important to note that the sensor characteristics are changing with temperature, moisture and live cycle period, which is hard to introduce in the sensor models or to control. This would make comparison of different sensors fair and would make it easier to choose suitable sensors for different applications.

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Statement of Competing Interests

The authors have no competing interests

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