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Biomedical instrumentation based on piezoelectric ceramics

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Abstract

New sensors and actuators based on emerging transducer technologies can play a crucial role in the field of biomedical instrumentation and rehabilitation technologies. Piezoelectricity and transducers based on the piezoelectric effect might lead to the adoption of compact sensor and actuator solutions in this field. This paper addresses a review of piezoelectric and piezoresistive transducer applications in the field of biomedical instrumentation. As an emerging application field, the potential implementation of these transducers in inertial motion analysis is addressed. The potential applications for these devices are high but we will focus on piezoelectric sensors in the area of inertial and portable biomechanical measurement systems and on piezoelectric actuators in active orthotics.

Keywords: Sensors; Actuators; Biomedical applications; Piezoelectric properties; Transducers

1. Introduction

Piezoelectric and piezoresistive materials allow the construction of new sensors and actuators which have a number of applications in the fields of biomechanics, clinical medicine, sports, technical aids to compensate for physical disabilities, sport devices, ergonomics and the evaluation of biomechanical loads at the workplace and, finally, future leisure applications of these devices can be foreseen as their cost is reduced and their use widespread.

It can be considered that the use of piezoelectric and piezoresistive accelerometers started in the eighties with the low weight low cost uniaxial accelerometers. They were applied to measure vibration (ergonomics), impacts (such as the heel-strike) and also other activities. However, the use of inertial sensors in biomechanical measuring application, remained marginal until the apparition of new devices such as the low mass piezoelectric gyroscopes that allow the encapsulation in a small size box of an ensemble of 3D gyroscopes and accelerometers.

The use of pressure sensors to record the contact forces between different parts of the body and the support surfaces started also in the eighties. Two applications were focused on the measurement of the pressures under the plantar aspect of the foot and under the supporting areas of disabled people that must sit down or lie during prolonged periods of time. The interaction of the human with the environment in terms of forces can also be monitored by means of piezoelectric solutions. In this regard, the three-dimensional interaction force at the foot during walking is a typical example of an application field that has been consolidated with, for example, piezoelectric ground reaction force plates.

A major limitation of current measuring devices in biomechanics is that they often restrict the experiments to a limited measurement field within the laboratory walls, thus limiting the natural execution of movements such as walking or running.[1] However, it is very useful to measure the movement under real environments and with longer time spans. An example of this fact is the analysis of the variability of gait, which could be a powerful indicator of gait stability problems and its use is growing rapidly in the last year.[2] A new measuring technology which enables ambulatory measurements will allow a significant scientific breakthrough in the field of biomedicine or robot for human interaction. Inertial sensors based on piezoelectric accelerometers and gyroscopes might be this technology as they would enable ambulatory biomechanical measurements.

All the above presented examples are sensor instances of piezoelectric transducer potential applications. Advanced actuators might also benefit from the driving characteristics of the converse piezoelectric effect. The field of rehabilitation technologies is plenty of potential applications in which the advent

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of compact, lightweight, efficient and low power actuators would make the difference for feasible rehabilitation devices. One emerging example of this is the field of active orthotics.

This paper addresses a review of piezoelectric and piezoresistive transducer applications in the field of biomedical instrumentation, mainly focused on the rehabilitation robotics field. The potential applications for these devices are high but we will focus on piezoelectric sensors in the area of inertial and portable biomechanical measurement systems and on piezoelectric actuators in active orthotics.

2. Requirements for biomedical instrumentation: focus on biomechanics

The requirements of piezoelectric sensors for biomechanical monitoring depend on its application, either to measure the kinematics or the kinetics.

2.1. Kinematics

The current standard to measure the biomechanics of motion is based on optical systems. These systems provide the joint angles without integration. The major drawbacks are the error induced by the motion of the markers mounted on the skin and the limitation to measure in a restricted field of vision of the cameras. An emerging technology to substitute optical motion-measuring systems is based on solid state inertial sensors comprising accelerometers and gyroscopes. These sensors can be used outside of the laboratory in the real environment of the patient. These systems provide a direct measure of the angular velocity and the acceleration of the body segment they are attached to. However, the segment and joint angles have to be calculated by integration, which suffers form drift, with the help of a biomechanical model of the body which introduces further errors. Although recent work has successfully implemented processing routines to suppress drift,[3] new developments in the sensor technology are needed in order to outweigh optical motion measuring systems. For instance, the increase in accuracy and precision of these inertial sensors or the integration of wireless gyroscopes and accelerometers in 3D with low mass in a body area network (BAN). At this point, they should, at least, match the specifications currently available by optical measuring systems.

2.2. Kinetics

The piezoelectric ceramic sensors are widely used for kinetic measurements. There are several commercial pressure sensors to measure the contact pressures between different body parts such as the plantar aspect of the foot or the back. Up to date, the commercial pressure sensors are 1D and cannot record the shear forces between the skin and the contact surface (shoe insole, anti-scar cushion).

Two important factors determine the use of pressure sensors:

1. Spatial resolution: Given by the number and size of the discrete sensors per unit area and that should be around 10 mm in order to measure adequately the peak pressures under the foot.
2. Temporal resolution: Depending on the application the low frequency components could be captured at 100 Hz. However, recording impacts (such as the heelstrike) would require sampling frequencies of 0.5–1 kHz.

The vertical pressure information is very useful for the design of orthopaedic footwear (e.g. diabetes) or anti-scar cushions. However, the measurement of the shear forces, which is crucial from a biomechanics point of view, is still an open problem, despite of the long-standing efforts of several research groups.[4]

3. Requirements for biomechanical actuation

The new generation orthotic and prosthetic devices have started to include active elements capable of providing or removing energy to compensate and enhance human function. The fields of application of biomechanical actuation are clinical (technical aids, orthoses and prostheses), sports (training) or as a human performance enhancer in ergonomics, military or even leisure purposes.

With respect to the ranges of moments, forces and powers the requirements of biomechanical actuators are given by the largest moments applied by the human body. For instance, during gait, one of the most relevant applications, the largest moments are about two times body mass.[5] The frequency requirements are not very high. For instance, in the motion of the joint of the arm the maximal frequency is 6 Hz.

In this respect, piezolectric motors are a promising technology for this type of actuators as they can be portable, with low mass, small size, and low consumption. Two important aspects of these actuators are related to safety and controllability. In this respect, the ranges of motion and the maximal forces should not exceed physiological ranges that could cause any injury to the user.

4. Electroceramic actuators in biomechanical applications

Actuators and (micro)drives play an important role in mechatronic systems in general, they can be regarded as the central component of motion control systems in that they usually impose limits to the overall performance (precision, dynamic range, size and weight) of most implementations. This takes particular relevance when dealing in particular rehabilitation systems.[6] The field of rehabilitation can be regarded as a distinct application area in terms of requirements for the driving technologies. Rehabilitation Robotics has been envisioned as technology for the restoration and functional compensation of people suffering from physical disability or disorders, either for the rehabilitation therapy or assistance of people. There are two common aspects to any rehabilitation device, namely, first, the intrinsic mechanical interaction between the device and the person, and secondly, wearability or portability of rehabilitation technologies.[7]

Both mechanical interaction and wearability are mainly affected by the driving technology. Again, for wearable solutions, the compactness (power/force density) of the driving technology is of paramount importance. In addition, since wearability and portability imply autonomy, the efficiency of the actuators is very important. A relevant aspect related to wearability is that of aesthetics and cosmesis. Invariably, when users are asked about subjective important aspects of rehabilitation technologies, external aspect and comfort is always mentioned. This has an impact of the rehabilitation system as a whole, but in particular it affect to the size, weight and, what is more important, the silent operation of the driving technologies.

The main limitation of rehabilitation devices as permanent assistive devices is the energy density provided by the actuators. It must be high, especially for the lower limb and the energy storage devices which must provide autonomy for several hours. Therefore, when developing portable robots a tradeoff between power and weight must be considered.

Piezoelectric based ultrasonic drives have reached a mature stage of development and can be regarded as potentially interesting solutions. Rotative travelling wave ultrasonic motors have become a commercial alternative to direct current electromagnetic motors. Power delivery is obtained in the low speed, high torque/force range, and thus giving rise to compact direct drive solutions. In addition, piezoelectric drives are silent and thus particularly suited for aesthetic requirements. The dynamic range of piezoelectric based drives is also relevant. In the case of the direct application of the inverse piezoelectric effect, the driving bandwidth extends to very high frequency, further than the application requirements. If the piezoelectric based ultrasonic drives are considered, still comparative driving advantages can be found with regards to electromagnetic drives. In particular, recent analysis of impedance controlled ultrasonic motors for rehabilitation robotics has shown a driving bandwidth up to approximately 20 Hz, 20% higher than the DC electromagnetic drives.[8] Some examples of devices based on piezoelectrics actuators are the activation of upper limb prosthetic devices. Upper limb prosthetic devices are aimed at substituting the manipulative functions of a lost upper limb. In order to provide manipulation capability, a prosthetic hand should involve as many as possible active joints. This in turn has direct consequences on the weight, size, autonomy, control requirements of the prosthetic solution.

Another representative example of the rehabilitation field is that of exoskeleton devices. Exoskeletons are external structures that act mechanically in parallel to a body segment to restore lost function. Exoskeletons are used to stabilize human gait in cases of muscle weakness following neurological disorders and they have been proposed as a means to cancel pathological tremor. Let us focus on the analysis of the drive requirements for the case of orthotic management of pathological tremor. The implications of this application on the requirements to the driving technology are to some degree similar to the previous case, i.e. all aesthetic and cosmetic considerations are applicable. Functional requirements are somehow different. In the orthotic cancellation of tremor, the biomechanical characteristic of the upper limb are modified to obtain a filtering action. In order to do this, and due to the particular characteristics of tremor, three main characteristics are imposed to the driving system, namely, a dynamic range up to 12–15 Hz, a good response at low speed, a high power density (as a trade-off between force and speed).

The main challenge in this technology is its control. The main control issues in resonant piezoelectric actuators are maintaining the resonant operating point irrespective of disturbances and matching the electrical impedance between the controller and the actuator for efficient operation. The main crucial control aspects in nonresonant drives are compensation of hysteresis and linearization.[10]

5. Electroceramic sensors in biomechanical applications

Kinematic and kinetic data obtained by biomechanical analysis is increasingly being used and required in active prosthetics/orthotics control systems. Several groups have used gyroscopes in order to obtain biomechanical information since human motion is rotational about joints and gyroscopes measure rotational motion.[9] During rotations, the gyroscope senses the mechanical deformation of an internal vibratory prim caused by the Coriolis force. It delivers an output voltage which is proportional to the absolute rotational velocity around its active axis. Gyroscopes sensors are classified as inertial sensors. Inertial sensors give an output signal proportional to its own motion respect to an inertial frame of reference, allowing the fabrication of motion sensors “internally referenced”. Micromachining techniques make possible the development of precision inertial sensors with a lower price and standard characteristics similar to those of integrated circuits, suitable for ambulatory applications. The main drawback of using gyroscopes has been its cost. The use of velocity as information to perform biomechanical analysis is important under a number of circumstances, i.e. an integration is needed to obtain angular displacement and a derivation is needed to obtain angular acceleration. At present, there is no triaxial angular rate sensor (gyroscopes) commercially available. The research for the development of such sensor based on ceramics is an activity field. Such sensor could easily be incorporated into designs requiring general-purpose triaxial angular rate measurements in a miniature size, for instance the biomechanical analysis of the lower limb joints,[10] see Fig. 1.

The use of piezoelectric ceramics to obtain kinetic information could be illustrated by the use of a piezoelectric sensor as a force transducer for plantar pressure measurement during human walking, see Fig. 2. The first description of piezoelectric foot sensors was that by Hennacy and Gunther.[11] Piezoelectric materials are ones that develop a surface charge in an amount dependent on the magnitude and orientation of the existing stress. The ceramics had a high modulus of elasticity, which suggested that they would have a high frequency response and were unlikely to attenuate the forces between the foot and ground. They also had high linearity and low hysteresis.[12] High spatial resolutions have been achieved using an array of sensors embedded in a flexible elastomer to produce an instrumented insole. Actually, the sensors developed to measure the plantar pressure are limited to the measurement of the normal force. The development of a triaxial sensor able to measure stresses at the surface of the foot is important under several applications, for instance for the control of Knee articulation of active exoskeletons. The

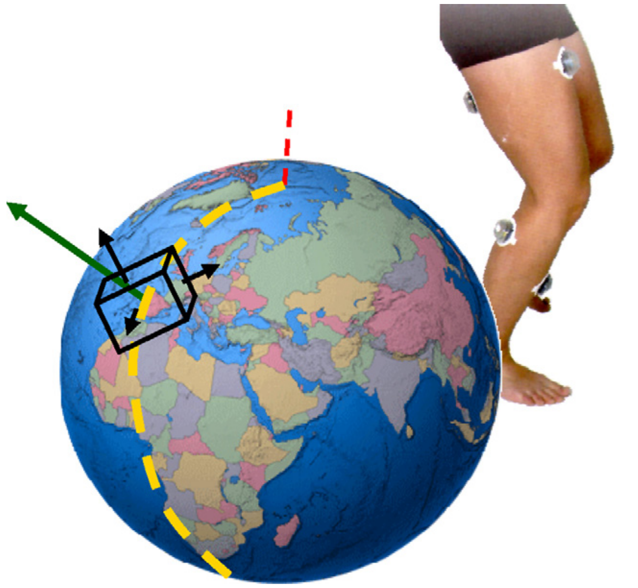

Fig. 1. 3D inertial sening: 3D piezoresistive accelerometers to be used as inclinometers, 3D piezoelectric accelerometers to determine segmental acceleration 3D Gyroscope systems for 3D angular velocity.

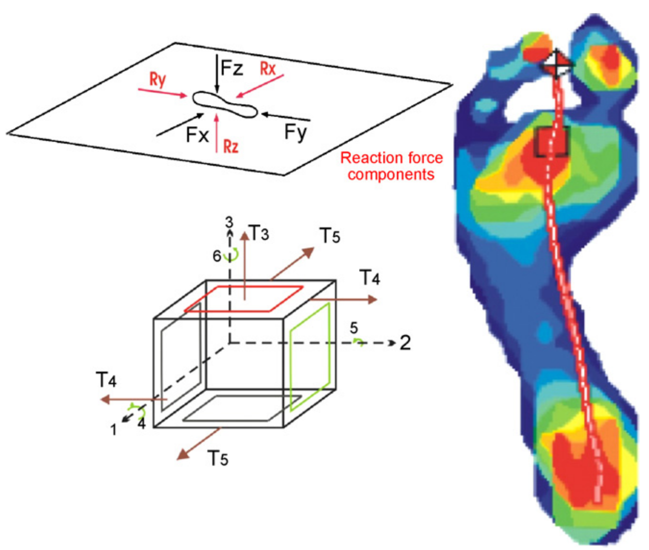

Fig. 2. 3D force distribution at feet dutring gait. Solution: use of piezoelectrics or piezoresistors poled in the tree orthogonal axes or the use of orthogonal electrodes on the same transducer.

development of such sensors could be achieved by the use of piezoelectric ceramics.[12]

6. Conclusions

The present paper introduced a review of the possible application of the new sensors and actuators based on piezoelectric and piezoresistive materials in of the rehabilitation robotics. In the paper we have presented some applications already developed based on piezoelectric sensors and actuators. In addition, the main requirements of possible applications are defined. The potential for new implementations is high, the challenging features to be accomplished in the application field are sound. All these make the medical (and rehabilitation) field a very attractive application domain for ceramics technologies.

Alternatively, other emerging transducer technologies have been proposed in this application field. Pneumatic or hydraulically powered implementations of active catheters have been proposed. In addition, novel actuator technologies, still not reaching a mature stage of development (shape and magnetic memory alloy drives, electroactive polymer based drives. . .) are subject to research. Amongst all these technologies, piezoelectric transducers appear as one of the most promising and mature technologies in the biomedical field.

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