WEARABLE HUMAN BODY JOINT AND POSTURE MEASURING SYSTEM

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Abstract: In many medical applications, especially the orthopaedic setting, ambulatory, monitoring of human joint angles could be of substantial value to improving rehabilitation strategies and unravelling the pathomechanics of many degenerative joint diseases (e.g. knee osteoarthritis). With the ageing of the population and increasing incidence of obesity, the prevalence of degenerative joint diseases is increasing (e.g. knee osteoarthritis is the single most common cause of pain and disability in middle-aged and older adults. As an example, In case of osteoarthritis rehabilitation, it is critical to monitor the loading of the affected joint during activities of daily living (ADL). These measurements allow monitoring of daily activity patterns, joint angles and walking patterns, which could be of use in adjusting the applied therapy depending on the results measured.

1 INTRODUCTION

In many medical applications ambulant, continuous monitoring of human joint angles offers some appealing added value to existing diagnosis and rehabilitation means, particularly in areas such as orthopaedics where monitoring the progress of the therapy provides more insight regarding therapy effectiveness. In case of arthritis rehabilitation, for example, it is desirable to support the recommended therapy by objectively monitoring the behaviour of the patient outside the clinic or hospital. Based on these measurements the specialist may check the exact exercise of the patient and subsequently adjust the applied therapy as necessary depending on the results. In this case the walking pattern of the knee joint was monitored as the most relevant to pathologies of this nature.

In more complex situations, for example with lower back pain prevention and/or rehabilitation, the level of bending in all directions of the lower back and the corresponding velocity could also be monitored preventing situations that should be avoided occurring by giving direct feedback to the user.

As a consequence a number of publications have reported ambulant instrumentation in recent years (Gransier, 2010), (Riskowski, 2009). However, only very few wearable systems are accurate enough in a dynamic situation when, for instance, the user is walking freely around. On the other hand there are several systems measuring human joint angles and

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posture in a laboratory setting which are not of direct interest in this study.

Comfort, accuracy and a user friendly interface are key elements for such a device to work successfully and be accepted in the medical world. The basic element of the measuring system introduced here is a very flexible, textile integrated bending sensor. Several of these basis elements may be combined in order to measure multi-dimensional joints or more degrees of freedom of the human body.

In the next sections the basic element required to measure bending is described.

2 BENDING SENSOR

2.1 Single Bending Sensor

Measuring bending in our setting is based on the change of electrical inductance of a very simple coil (a loop of a conductive wire). It appears that the inductance of a coil changes as the form of the coil changes. The mutual inductance by a filamentary circuit *i* on a filamentary circuit *j* is given by the double integral:

$$L \approx \left(\frac{\mu_0}{4\pi} \oint_{C} \oint_{C'} \frac{ds \cdot ds'}{|\mathbf{R}|} \right)_{[\mathbf{R}] \geq a/2} + \frac{\mu_0}{4\pi} lY \qquad (1)$$

where μ_0 denotes the magnetic constant ($4\pi \mathrm{x} 10^{-7}$H/m), C and C' are curves along the wires, $\mathbf{R}$ is the distance between two points on respectively C and C'. The vectors ds and ds' represent vectors along C and C'. When $\mathbf{R}$ becomes zero the above equation becomes infinitive and therefore there is an extra condition that $\mathbf{R}$ has to be larger than half the thickness of the wire *a*. In that case the inductance is only dependant on the radius a and its length l and some factor Y denoting the current distribution through the wire (typically Y=1/4). When the form of the coil changes, the orientation of ds and ds' changes and probably the distance between them too. That results in a change of the inductance of the coil.

As can be seen in equation (1) the mutual position and orientation of the wire segments determine the total inductance of the coil. It is these elements that vary when the coil bends and thus consequently changes the inductance correspondingly. The wire used in this sensor is very flexible and thin and integrated in a carrier e.g.. knee brace, t-shirt, strap etc.

In the case that the bend of the coil is directly connected to a single bending angle of a human joint (knee, elbow etc.), a simple calibration can be used to translate the bending inductance readings into an absolute angle value. Calibration can be done using a reference measuring system that simultaneously measures the joint angle.

However in some cases, where the carrier may be minimally shifted due to movement, the system can be automatically recalibrated based on extra information from accelerometers mounted on the carrier.

2.2 Automatic Recalibration

In many applications where the bending sensors are firmly attached to a body joint the translation from inductance reading into joint angles can be done once based on some discrete calibration measurements. In particular in the case of a single joint the calibration can be performed using mechanical goniometry.

However, wearing a sensory system for a longer time in a day inherently implies local shifting of the system on the body, hence a discrepancy of the calibration of the sensor. In addition, by fitting or "putting on" the sensory system in a non-reproducible way, the user introduces an additional error in the calibration. To account for this an automatic calibration was introduced based on extra sensors mounted around the joint. A set of two tri-axial accelerometers is placed above and below the joint. When the user is in a steady state (sitting, standing etc.) the readings of the accelerometers may be used to calculate the absolute angle of the joint. In static situations the accelerometers are only measuring some proportion of the gravitational force. Based on this, the angle between the accelerometers is calculated. In dynamic situations (walking, running etc.), the accelerometers "see" simultaneously the gravitational force and the human movement. In this case the calculation of the joint angle is not possible using the accelerometers. For this case the inductance measurement is used for calculating the joint angle. Every static situation during the day is used to (re)calibrate the bending sensor compensating for any changes of the bending sensor attachment on the human joint.

In summary, during static situations the accelerometers are used to calculate the absolute joint angle and calibrating the bending sensor, and in dynamic situations only the calibrated bending sensor is used.

2.3 Validation of a Single Bending Sensor

The goal of the validation study was to quantify the knee angle error during normal activity (i.e. standing, sitting, and walking). Therefore a single bending sensor was attached to a knee brace with the aim to measure the knee joint angle. In Figure 1 a knee brace is depicted where the inductance loop is attached.

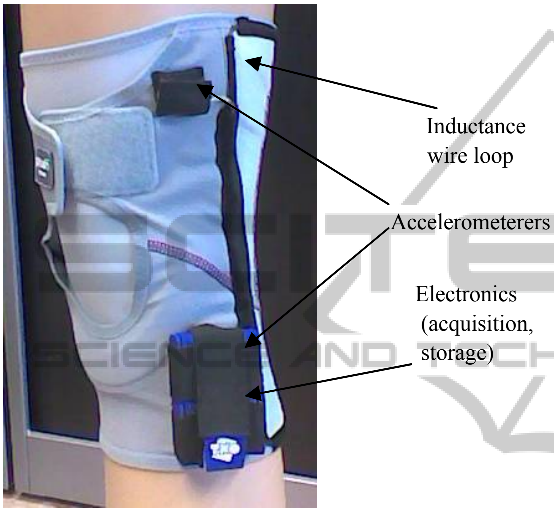

Figure 1 Knee brace including bending/angle sensor.

Besides this the two accelerometers to be used for the automatic calibration are attached on the upper and lower parts of the brace. For validation purposes, the knee angle was also measured using an external VICON Camera system (http://www.vicon.co). Figure 2 depicts a measurement where the VICON knee angle and the angle measured can be compared.

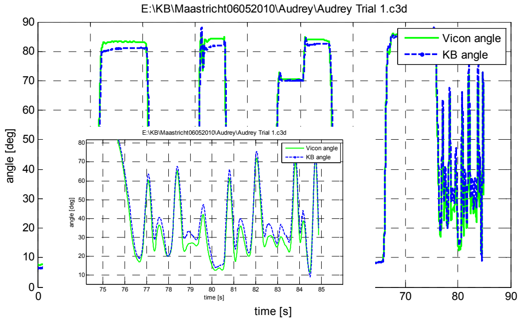

Figure 2: Measured and reference knee angle (static and dynamic part).

The protocol followed consisted of a series of common movements i.e *standing, sitting (twice), leg bending at four positions during sitting, standing, sitting, standing and walking*. A number of users have been measured (5 reported in this paper), where mostly five measurements have been performed per user. A typical sample of the validation results are shown in Table 1 depicting the maximal absolute value of the error which is the difference between the measured angle and the reference angle.

Table 1: Validation Result.

person	a	b.	c	d	e
Mean	1.851	2.327	2.579	3.085	3.973
Abs.	1.559	2.617	2.093	3.577	3.504
Error	1.804	3.239	1.765	2.970	2.719
[deg]	1.464	2.313	2.446	3.204	2.130
	1.421	2.051	2.186	4.246	2.523

An extended description of the validation procedure and the corresponding validation results of this specific single bending sensor are reported in (Gransier et al., 2010) and (Riskowski et al. 2009).

2.4 Multiple Bending Sensor

A combination of the aforementioned single bending sensor can be used in the case of measuring more complex human joints, i.e. shoulder, wrist etc. Not only joints but also body posture i.e. torso, can be measured using a number of single bending sensors.

Suppose a human body part, the lower back for example, which should be measured in terms of three angles (flexion-extension, lateral flexion-extension and rotation). Using a carrier, in this case a shirt, it was possible to attach a number of wire-loops on strategic positions around the body (see Figure 3).

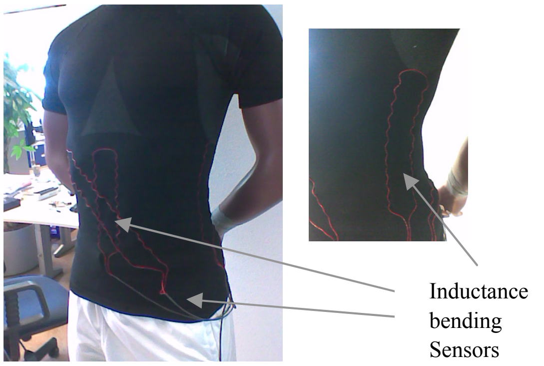

Figure 3: t-shirt crrier of osture multiple bending senor.

Measuring with a multiple bending sensor consists of the following steps:

- Calibration or modeling the single bending sensors separately
- Calculating the body posture based on the readings of the single bending sensors.

2.4.1 Calibration/Modelling

Calibrating a bending sensor really means modeling the behavior of the inductance loop as function of the angles or degrees of freedom of the body part under consideration. Suppose a model of a single bending sensor:

$$L_i = S(\mathbf{p}, \mathbf{a}) \tag{2}$$

Where $\mathbf{p} \in R^m$ represents the parameter set and $\mathbf{a} \in R^n$ the angles of the body part under consideration. Here m number of parameters and n degrees of freedom is assumed. Commonly there are three degrees of freedom in the case of most human joints and body parts.

Based on a number of measured inductances and the corresponding body posture, the model can be fitted by tuning the parameters.

2.4.2 Measuring Body Part Posture

Based on the calculated models for a number of bending sensors it is then possible to calculate the body part posture. The relationship between bending sensor readings and body part posture is of a very complex, non-linear, character. The problem of calculating the body part posture has bee resolved to provide an estimation of the real posture[1].

2.5 Validation of a Multiple Bending Sensor on a Dummy Body Torso/Spine

Comparable to the single angle bending sensor, for the multiple bending sensor a carrier was chosen to attach the inductance wires on the body in the form of a tightly fitting elastic t-shirt. Before the system could be implemented on the human body, a dummy torso model was used to validate the modeling and measuring method described in the previous sections. An image of this torso model can be seen in Figure 4. A flexible column represents the human spine, with more rigid protruding discs modeling the skeleton ribs. On this dummy model flexible conductive wire loops are positioned in such a way so as to form a multiple bending sensor. By measuring with a VICON camera system and simultaneously with the multiple bending sensor the three degrees of freedom of this model (two bending directions and one rotation around the spine) we acquire data for modeling and validation purposes. In this instance a model has been fitted for every single bending sensor separately. In Figure 5 the inductance models of the bending sensors are depicted as described by equation (2). Based on these sensor models the validation of the multiple bending sensor has been investigated. The three degrees of freedom of posture are then calculated.

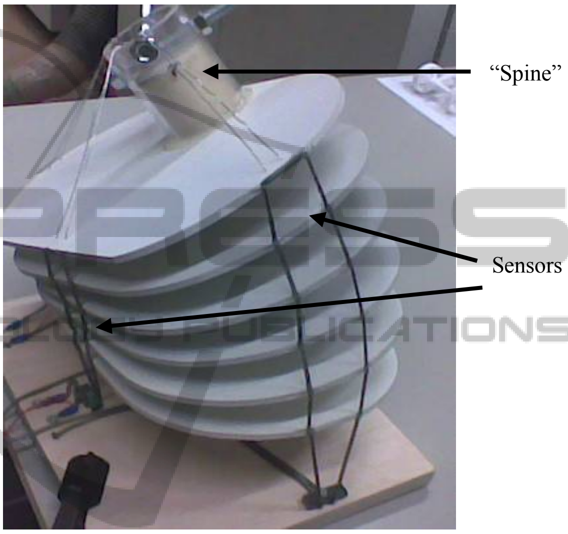

Figure 4: Low back model.

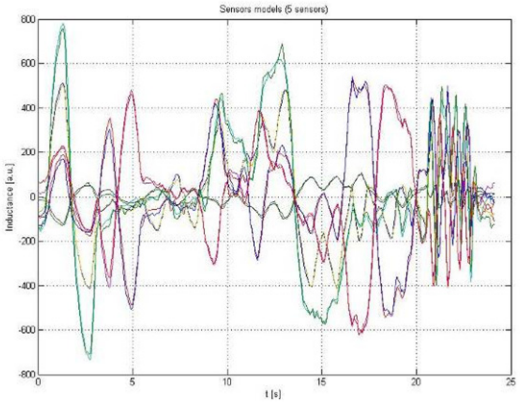

Figure 5: Models of bending sensor model.

The error between the real angles and the calculated angle in Figure 6, Figure 7 and Figure 8 for the three separate degrees of freedom in reference to one sensor.

As appears, in x- and y-direction the angle error is less than ±2 degrees, and in z-direction less than ±6 degrees.

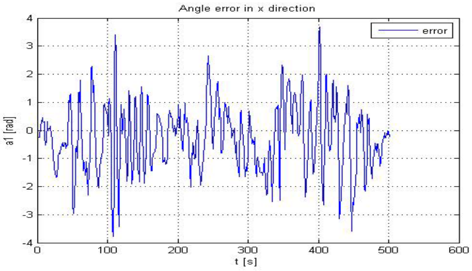

Figure 6: Angle error in x-direction.

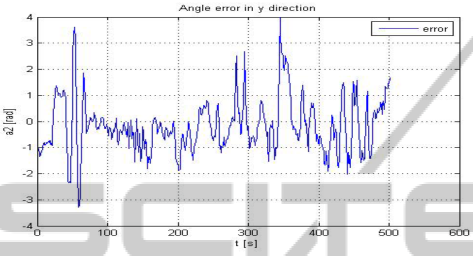

Figure 7: Angle error in y-direction.

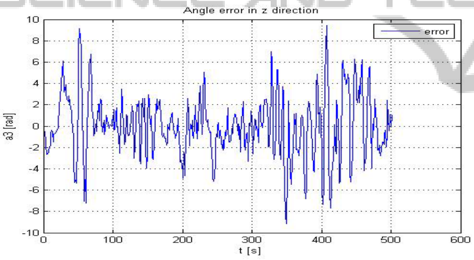

Figure 8: Angle error in z-direction.

3 CONCLUSIONS

A single bending human joint angle sensor system is presented. The measuring accuracy of ±2 degrees gives unique and sufficient basis for clinical ambulant applications basis for further exploitation of the technology.

In case of more complicated body moving parts (shoulder, trunk etc.) a combination of single bending sensors may be used to measure the relevant degrees of freedom of the body part under consideration. The accuracy results for flexion-extension and lateral flexion-extension are very promising (<2 degrees). In case of the torso rotation angle we report higher errors (<6 degrees) and depending on the application may meet the required accuracy. Further investigation using realistic sensor carriers i.e. t-shirt, is on going. Such a system (t-shirt including sensors, electronics etc) has already been built and tested.

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