An Implantable System for Angles Measurement in Prosthetic Knee

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SUMMARY

In this work we designed and tested an in-vivo measurement system of prosthetic knee joint angles. The system included a small permanent magnet in the femoral part and three magneto resistance sensors placed in the polyethylene part. The sensor configuration was defined based on sensitivity analysis, signal to noise ratio, saturation of sensors and movements constraints. A mapping algorithm was designed to estimate the orientation of the femoral part in sagittal and coronal plane. For validation the prosthesis was placed in a mechanical simulator equipped with reflective markers tracked by optical motion capture.

INTRODUCTION

There are few works in the area of instrumented prosthesis. The most important one was proposed by Bergmann et al [1] for the hip joint and more recently for the knee joint where strain gauges inside the tibial tray measured the six load component [2]. Their study includes detail analysis of force and moments for different activities [3]. D'Lima et al. designed another implantable telemetry device for the measurement of tibial forces [4], and recently used it during exercise and recreational activities [5]. Load measurement was the main purpose of instrumented prosthesis since the direct measurement of the force can only be through implanted sensors while other biomechanics quantities such as kinematics can be measured by skin mounted markers or sensors. Nevertheless, motion capture with skin mounted markers or body worn sensors suffer from the soft tissue artifact (STA). Therefore, considering the current progress in instrumented prosthesis, having implanted movement sensors in the prosthesis could be a promising solution to avoid STA. Currently, there is no instrumented prosthesis with movement sensors. The aim of this study was to devise a measuring system that can be implanted into knee prosthesis for the measurement of orientation of the joint during daily task. The system was designed in order to be compatible with existing commercialized knee prosthesis, offering in this way minimum change in the design of prosthesis.

METHODS

Sensors' configuration: The F.I.R.S.T knee prosthesis (Symbios, CH) was used for this study. In order to impose as less as possible change in design of the prosthesis and be compatible with most prosthesis, we decided to insert all electronics and sensors into the polyethylene (PE) part of the prosthesis. This offers also more flexibility for remote powering and efficient communication [6]. Using the fact that human body is transparent to magnetic flux and the negligible effect of CrCo alloy-based prosthesis on magnetic flow, we chose anisotropic magnetic (AMR) sensors to estimate joint orientation. A permanent magnet as a passive source was placed in femoral part (FP) of the prosthesis where it pointed to PE, and three AMR sensors (HMC1053) in PE were used to measure the direction of flux in known relative geometry of the PE (Figure 1). This way, movements of the femur relative to the PE result in change of magnetic flux measured by the sensors. In order to evaluate the sensitivity of the sensor configuration to magnetic field, the intensity of magnetic flux was measured in term of magnet strength and lengths as well as its distance to the sensors. Finally, the electronics and sensors were devised to be inserted deeply, more than 6mm from the top of PE to guarantee the safety issues of wearing.

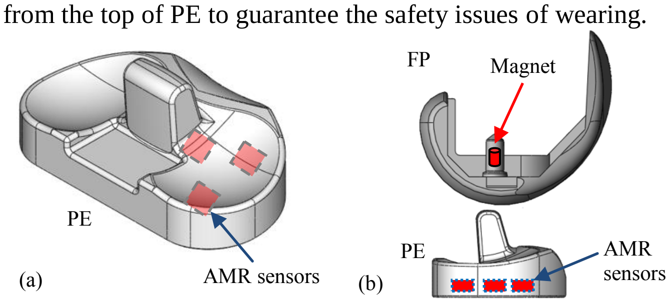

Figure 1: (a) AMR sensors inside polyethylene (PE). (b) Magnet in femoral part (FP) and sensors location (PE)

Mechanical knee simulators: The instrumented prosthesis where used in a mechanical system which simulates 3D rotational movements of the knee. Optical motion capture (Vicon, UK) and reflective markers on known geometry of the simulator were used to track the exact kinematics of the prosthesis (Figure 2).

Figure 2: Mechanical simulator and instrumented knee prosthesis (F.I.R.S.T) equipped with reflective marker.

Mapping algorithm: Artificial neural networks (NN) were used to map the magnetic measurements to the kinematic measurements obtained by optical motion capture. The NN solution was preferred mainly due to i) the specific nonlinearity of each sensors making the calibration procedure complex and ii) the absence of a physical model taking into account all geometric and magnetic features of the magnet. Observing the non-linear relation between crude magnetic signals and markers' trajectory, via correlation and mutual information analysis [7], we utilized a separate two-layer Perceptron (with 40-neuron in the hidden layer) to best estimate 3D trajectory of each marker.

Measurement: A series of 15 flexion-extension movements (mixed with different abduction-adduction) were performed. Each marker trajectory was estimated from optical motion capture and used to train the NNs. The training set included 75% of randomly selected data. The remained 25% of data was used to estimate and test the error of the angle estimation of joint angles on saggital and coronal planes, considering optical motion capture as reference.

RESULTS AND DISCUSSION

Figure 3 shows the intensity of the measured magnetic flux by an AMR sensor for three pairs of magnets-sensor (Ni-Cu-Ni magnets, all have 5mm diameters: 900gauss disk magnet 5mm length, 970gauss cylindrical magnet 8.47mm length, and 1Kgauss cylindrical magnet 2.54cm length). We observed a specific sensitive range of distance depending on length and strength of magnet. Besides, increase of magnet-sensors distance results in decrease of signal to noise ratio and precision. Moreover, in order to avoid sensor's saturation, the magnet and sensor must not reach close vicinity. Based on these observations, the mentioned disk magnet was selected, and the distance between sensors in PE was fixed in order to guarantee an approximate distance of 1.8 cm to 3.4cm with magnet (inside the sensitive distance range) during 0 to 60 degree flexion of the prosthesis. Considering this sensor configuration, after the training of mapping algorithm the errors on flexion-extension and abduction-adduction of the mixed movements were estimated and reported in Table 1. These preliminary results confirm that angles can be accurately estimated especially in case of abduction-adduction in which skin-mounted measurement systems have not achieved a satisfactory accuracy. In a future step internal-external rotations can be estimated with similar methodology.

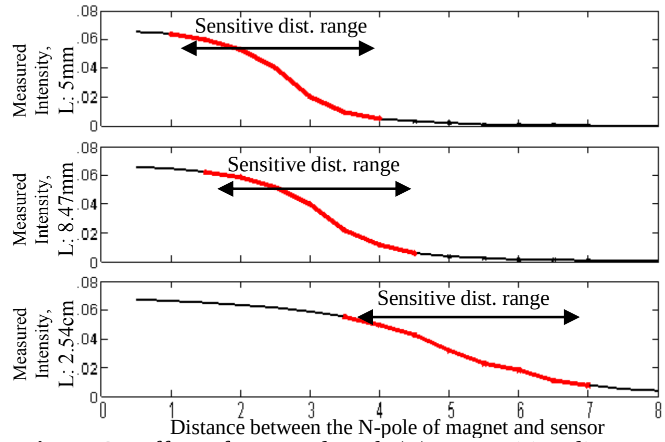

Figure 3: Effect of magnet length (L) on sensitive distances for an AMR sensor (sensitive dist. is indicated by an arrow).

CONCLUSIONS

A novel internal kinematics measurement system for knee prosthesis was proposed which can be used to estimate the kinematics of instrumented knee prosthesis. Such a system can offer actual movement of a prosthetic knee without soft tissue artifact. The results can be useful for the design of new prosthesis, in vivo measurement for prediction of failure and can be combined with force measurement for a better evaluation of knee joint biomechanics. Further investigation is necessary to integrate all electronic components including powering and data communication into the PE part.

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Table 1: Mean (E), standard deviation (STD), RMS and maximum (MAX) of the joint angle error in Saggital plane (flexion-extension) and Coronal plane (abduction-adduction).

Joint Angle	**Estimation Error**			
Angle [Range]	**E(error)**	**STD(error)**	***rms*(error)**	**Max(|error|)**
Flexion-extension [138^o 192^o]	-1.54^o	1.77^0	2.35^0	5.11^0
Abduction-Adduction [-8^o 4^o]	0.23^0	0.20^0	0.31^0	0.93^0