Force and torque sensors for orthopedic applications

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Navigated planning and surgery techniques are well established in joint replacement procedures. They offer the possibility to operate more precisely and lead therefore to better results. The intraoperative measurement of forces like ligament tension or milling forces during the operation can further improve the accuracy and yield more reproducible results. Integration of force and torque sensors for multiple applications is one of the aims of the OrthoMIT project. Some examples of applications are shown here.

With the increase of the expectancy of life of an augmented need of hip and knee arthroplasties and also revision operations becomes necessary. The prolonged use of joints often leads to failure and a replacement is needed. Arthrosis, especially in the hip and the knee joint, is the major indication for the replacement of the affected joint. Total joints prostheses offer pain relief and a better quality of life for the patients. To ensure the physiological positioning of the prosthesis, navigated planning and operation tools are on the market. They help the surgeon to place the implant in an optimal positon to increase the lifetime of an implant. Nevertheless post-operational complications are not uncommon.

In total knee arthroplasty the misalignment of tibial and femoral components and an incorrect soft tissue balancing are main reasons for premature implant failure or persistent knee instabilities. Tibiofemoral misalignment can be minimized with navigated surgical techniques [*1, 2*]. On the other hand soft tissue balancing means the right adjustment of the ligament tensions. The intraoperative measurement of ligament tension is carried out manually or with basic mechanical tools [3]. The most common methods include laminar spreaders or spacer blocks: after the bone cuts are carried out femur and tibia are distracted until a sufficient tension in the lateral ligaments is reached. Then the joint gap is measured and a suitable bearing is chosen according to the manufacturers guidelines and is inserted. Equalization of collateral ligament tension can be reached by release of the ligaments. The ligaments are cut unil the forces acting on the condyles are equalized. During the procedure the surgeon measures the forces from time to time by pulling the joint apart. It is obvious that this measurement method is not quantitative, reproducible and dependent on the surgeon.

For measurement of the condylar forces, a trial tibial inlay from Aesculap AG, Germany from the Columbus knee arthroplasty suite was equipped with three load cells per condyle. The inlay was cut in halves to be able to measure the condylar forces indepent from each other. The use of three load cells per condyle makes it possible to calculate the magnitude of the force and the point of force application. The values can be calculated by solving the mechanical equilibrium equations:

$$\Sigma F_i = -F_{condyle} \qquad \Sigma M_{x,i} = 0 \qquad \Sigma M_{y,i} = 0$$

Fig. 1: Sensor-integrated tibial inlay

The load cells are based on piezoresistive pressure sensors. These sensors are placed in stainless steel housing which is filled with a silicone gel. A force transmission cap compresses the gel if an external force acts on it and hence the pressure can be measured. It is possible to measure forces up to 150 N with a single load cell with a linear dependence. The complete inlay can be seen in Fig. 1.

Measurements with the inlay on compression test machine show good results. The applied force was measured with the inlay.

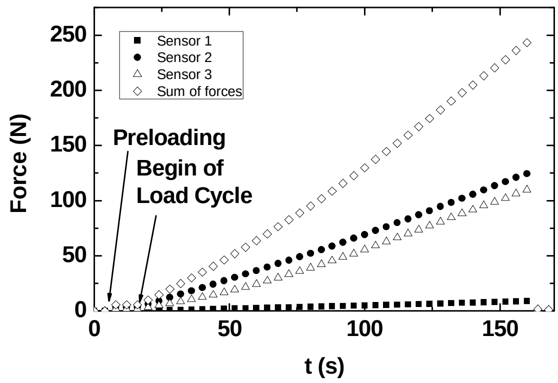
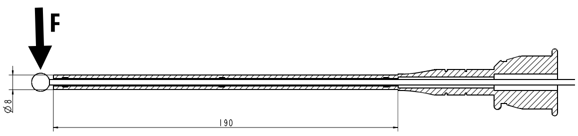
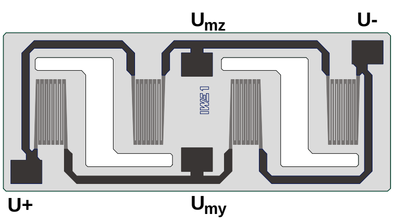


Fig. 2: Forces acting on one condyle in a compression test

Also in total hip arthroplasty revision surgery force measurement can play an important role. Cemented total hip arthroplasty stems provide an excellent long-term stability [4] and offer a fast mobility after the operation for the patients. But in case of a revision surgery, the old bone cement plug has to be removed completely. Otherwise it will result in diminished strength at the interface between the bone and the revision implant. This finally causes premature failure of the implant. Since the bone cement plug is in the femoral canal and cannot be directly seen, navigated surgery gives very good results bone cement removal. The bone cement can be reconstructed by multiple X-Ray pictures [*5, 6*]. By a navigated milling tool, the bone cement can be removed. The instrument is tracked by an optical tracking system. But only the part outside the body of the instrument can be tracked, because a line of sight is needed between the tracking camera and the tracking marker. Beside that the size of the markers has to be rather large for a high accuracy. The position of the mill in the femoral canal is calculated by a constant offset vector from the center of the tracking marker. By this method elastic deformation of the milling tool in response to the milling forces is neglected. This error can lead to an incomplete removal of the bone cement plug or to an excessive removal of bone material or to perforation of the femur. Both cases lead to a prolonged morbidity or premature failure of the implant [7]. The deformation of the instrument can be measured easily by strain gauges. These strain gauges are applied on the milling tool by an adhesive and connected to a microcontroller based electronic circuitry that processes the sensor data and is able to send it to the navigation system for position correction. To ensure a good alignment of the four strain gauges and to minimize the number of external wirings, the four needed strain gauges are placed on a single foil and connected in two half-bridge configurations with a common power supply. The milling shaft can be considered as an elastic beam that deflects under the influence of external forces as shown in the first picture of Fig. 3.





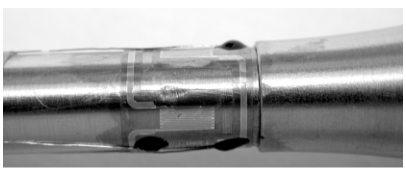


Fig. 3: Milling tool, sensor foil and sensor foil wrapped around the shaft of the milling tool

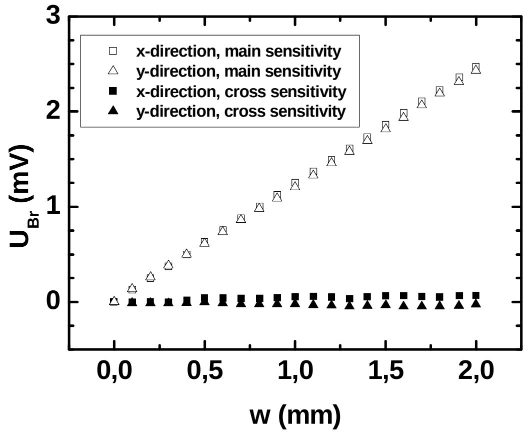


Fig. 4: Main sensitivity and cross sensitivity of strain gauge bridges in x and y direction

The strain gauges show a good linear dependence and only little cross sensitivity as depicted in Fig. 4. By solving the following set of two linear equations the deflection can be calculated from the two voltages U_{BR} of the strain gauge bridges:

$$\begin{pmatrix} s_{xm} & s_{yc} \\ s_{xc} & s_{ym} \end{pmatrix} \cdot \begin{pmatrix} w_x \\ w_y \end{pmatrix} = \begin{pmatrix} U_{Br,x} \\ U_{Br,y} \end{pmatrix}$$

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Aesculap AG, Tuttlingen, http://www.aesculap.de

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