MEASURING DEVICE FOR ON-LINE CALCULATING AND SCREENING OF KNEE JOINT FORCES

Hermann Schwameder, Robin Roithner, Erich Müller, Wolfgang Niessen, Christian Raschner, Universität Salzburg, Austria

INTRODUCTION: Many different locomotions and postures in sports cause loads on the different structures of the knee joint. A knowledge of these internal forces and moments are of decisive importance concerning preventive and rehabilitative aspects. The stresses on and within the different structures depend on the external bending moment, as well as on the kinematics of the knee joint. In the literature different methods for estimating these stresses are reported. In addition to the in-vitro-measurements (e.g., Buff et al., 1988, Miller et al., 1997) many mathematical models for calculating the internal forces within the knee joint have been developed (e.g., Moeinzadeh et al., 1983, Nisell, 1985, Yamaguchi/Zajac, 1989, Blankevoort et al., 1991, Loch et al., 1992, Gill et al., 1996). Nisell (1985) is the only one who estimates structure forces depending on external bending moments. The nomograms reported by him are inaccurate in that way as appropriate values are only given for knee angles between 0° and 120° in steps of 30°. The values in between have to be calculated by linear interpolation.
From the preventive and rehabilitative point of view an on-line calculation and visualizing of knee joint forces in real-time could guarantee important simultaneous feedback of loads and stresses on the different structures during training and performance exercises in several sports. This information is necessary for athletes, trainers, sports scientists and physicians to the same extent. Based on these considerations an existing 2D knee model should be adapted in such a manner that knee joint forces can be calculated and visualized in real time.

METHODS:

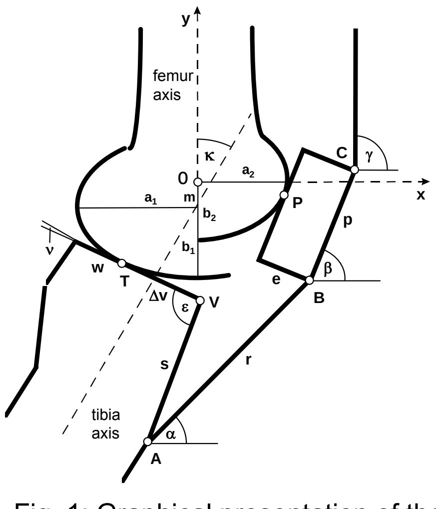

Fig. 1: Graphical presentation of the two-dimensional knee model 'Plakmos'

Knee model (Plakmos)

A fundamental requirement for on-line calculating the knee joint forces has been the determination of the kinematics as function of the knee angle κ. The basis of the 2D-model called 'Plakmos' (Fig. 1) is built by the 2D-model of Yamaguchi/Zajac (1989). This model has been completed by data from Nisell (1985) and ourselves (measurements of 20 x-ray pictures) and expanded for knee angles up to 120°. The femur condyles in both models are approximated by two vertically shifted ellipses of different size. The bigger one represents the area of the tibiofemoral joint and therefore keeps in contact with the tibia plateau, while the smaller ellipse describes the intercondylar groove on which the patella passes. The tibia plateau and the patellar ligament are modeled as a straight line of constant length and the patella is approximated as a rectangle. All parts of the model are assumed to be rigid and the friction at the contact points is neglected.

All relevant parameters needed for describing the kinematics of the knee joint have been determined for knee angles between 0° and 120° in steps of 2°. In a further procedure these data have been calculated as polynomial functions of the knee angle up to order 10 using non-linear regression technique.

Assuming quasi-static conditions the compression and tension forces can be calculated using systems of linear equations. The magnitude $|F|$, the direction (φ) and the point of application (x_F) of the ground reaction force F can be measured using a force platform. The position of F in relation to the knee joint yields the action angle τ of the tibiofemoral contact force F_t. As α is known the tibiofemoral contact force F_t and the patellar ligament force F_p can be calculated by the system

$$\begin{pmatrix} F_t \\ F_p \end{pmatrix} = \begin{pmatrix} \cos\tau & -\cos\alpha \\ \sin\tau & -\sin\alpha \end{pmatrix}^{-1} F \begin{pmatrix} \cos\varphi \\ \sin\varphi \end{pmatrix} \qquad (1)$$

F_t can be subdivided into the tibiofemoral compression force F_{ct} perpendicular to the tibia plateau and into the tibiofemoral shear force F_{st} in the direction of the tibia plateau. As the tibiofemoral contact point is assumed to be frictionless the shear forces only can be compensated by the cruciate ligaments. As they are not included into the model, the cruciate ligament forces can not be determined numerically.

The patellofemoral compression force F_{cp} and the quadriceps tendon force F_q can be determined by

$$\begin{pmatrix} F_{cp} \\ F_q \end{pmatrix} = \begin{pmatrix} \cos(90+\beta) & -\cos\gamma \\ \sin(90+\beta) & -\sin\gamma \end{pmatrix}^{-1} (-F_p) \begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix} \qquad (2)$$

If the knee angle κ exceeds 85°, the quadriceps tendon entwines the femoral groove and causes the quadriceps tendon compression force F_{cq}. Assuming frictionless conditions, at the contact area F_{cq} can be calculated by

$$F_{cq} = 2F_q \sin\left(\frac{90-\gamma}{2}\right) \qquad (3)$$

Using the described quasi-static and two-dimensional approach, 'Plakmos' offers the calculation of the following structure forces depending on an external bending moment: tibiofemoral contact force (F_t), tibiofemoral compression force (F_{ct}), tibiofemoral shear force (F_{st}), patellar ligament force (F_p), patellofemoral compression force (F_{cp}), quadriceps tendon force (F_q) and quadriceps tendon compression force (F_{cq}).

The kinematics of 'Plakmos' and specific structure force ratios coincide with the knee models reported very closely. Examples of comparisons (patella angle β, ratio between the patellofemural compression force and the quadriceps tendon force F_{cp}/F_q) with similar models reported by van Eijden et al. (1986), Yamaguchi/Zajac (1989), Gill et al. (1996) and Miller et al. (1997) are shown in Fig. 2 and 3.

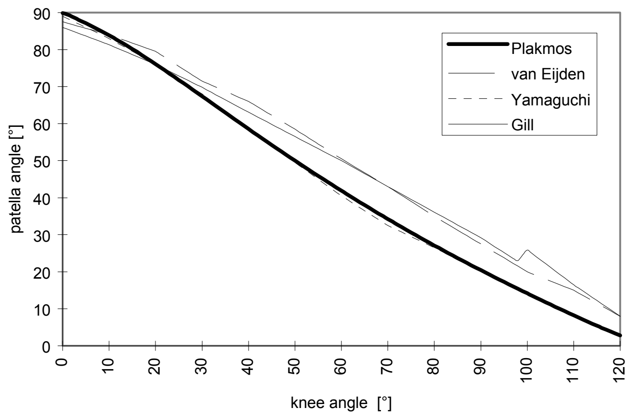

Fig. 2:
Comparison of the patellar angle β with data reported by van Eijden et al. (1986), Yamaguchi/Zajac (1989) and Gill et al. (1996)

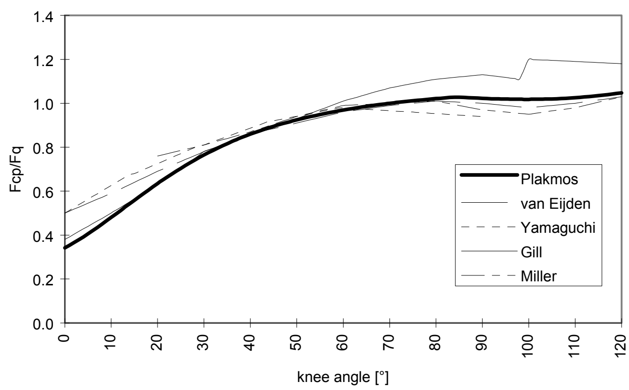

Fig. 3:
Comparison of the ratio Fcp/Fq with data reported by van Eijden et al. (1986), Yamaguchi/Zajac (1989), Gill et al. (1996) and Miller et al. (1997)

Calculation and visualization of the knee joint forces

The measuring device consists of a 3D force platform (AMTI) to determine the magnitudes, directions and application points of the ground reaction forces and two electronic goniometers to obtain the ankle and knee joint angles. The length of the shank and the measured ankle joint angle yield the displacement of the actual center of rotation within the knee joint in relation to the coordinate system of the force platform. The data collected serve as input for calculating the knee joint forces. As described above, the kinematics of the knee joint are given by 'Plakmos', using polynomial functions of the knee angle κ. The data collection (ground reaction forces, moments and angles), the calculation of the knee kinematics, the procedures for determining the knee joint forces and their visualization are carried out using the measuring software 'Dasylab'.

RESULTS: It could be shown that the calculation approach using 'Plakmos' as well as the measuring device - consisting of the force platform, the goniometers, the mathematical algorithms and the measuring software - are convenient for an on-line visualization of selected structure forces within the knee joint. The different errors caused by the measuring device have been estimated with appropriate

methods (mainly video analyses). The greatest errors occur in measuring the joint angles, while the data errors caused by the force platform are negligible. The input data errors result in relative errors of the structure forces between 2% and 8%. The errors caused by the restrictions and assumptions of the model (two-dimensional, rigid bodies, approximated shapes) are hardly assessable, but the high accordance with similar models reported (see Fig. 2 and 3) entitles us to apply 'Plakmos' in the manner mentioned above. This latter aspect is of negligible importance if different situations are compared relatively.
The utility and simplicity of the measuring system including 'Plakmos' has been demonstrated in comparative studies of knee bending movements with and without additional weights and different knee bending techniques.

CONCLUSION: From the preventive and rehabilitative point of view, knowledge of external loads and internal stresses on different structures of the human body are of decisive importance. On-line measuring and visualizing systems help athletes, coaches, sports scientists and physicians to estimate stresses on critical structures in postures and during locomotions. The system presented enables us to calculate and visualize structure forces within the knee joint during simple postures and locomotions in real-time. The advantage of the device is that athletes and patients can react immediately to excessive stresses by changing their techniques in an adequate manner. It is obvious that real-time feedback systems are one of the best possibilities to prevent athletes both in elite and rehabilitative training processes from excessive stresses and injuries.

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