A REAL-TIME MODEL OF THE HUMAN KNEE FOR A VIRTUAL ORTHOPAEDIC TRAINER

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Abstract *– In this paper a real-time capable computational model of the human knee is presented. The model describes the passive elastic joint characteristics in six degrees-of-freedom (DOF). A black-box approach was chosen, where experimental data were approximated by piecewise polynomial functions.*

The knee model has been applied in a the Virtual Orthopaedic Trainer, which can support training of physical knee evaluation required for diagnosis and surgical planning.

Keywords: Virtual Reality, Knee, Computational Model, Elastic Properties, Stiffness, Laxity, Orthopaedics

Introduction

Injuries, diseases, and pre- and post-surgical properties of the knee joint can be evaluated by performing different kinds of tests. These include passive movement tests in flexion/extension, varus/valgus, internal/external rotation, and anterior/posterior directions (Fig. 1) to determine mid-range laxity and end-point stiffness of the joint.

A lot of experience and practice is necessary to feel the difference between healthy and pathological joint properties and determine the correct diagnosis. However, due to limited access to patients an adequate training of medical students or young orthopaedic physicians is difficult. A knee joint simulator that comprises the properties of a healthy or pathological knee joint is expected to support training of physical knee evaluation required for diagnosis and surgical planning.

For this reason, we developed a knee joint simulator [4] that enables a user to touch and move a virtual shank and simultaneously observe the generated movement, feel the contact force, and hear sounds produced by the joint movement or the patient due to pain. Its features enable the user to assess the properties of the knee by testing the joint laxity and end-point stiffness in six degrees-of-freedom (DoF). In order to give a realistic impression of the occurring forces, the haptic feedback has to be performed at the high rate of 1000 Hz.

In this paper a real-time model of the human knee is presented. The stiffness characteristics of all rotational and translational DoF are considered. Since it was not necessary to get insight into physiological knee function, a black box approach could be applied to fulfil the requirements for a realistic force feedback.

Modelling Approach

The anatomical structures surrounding the knee joint (ligaments, tendons, joint capsule, etc.) determine the mechanical properties that can be investigated when moving the shank relative to the thigh. In this study a model was derived, that describes the passive elastic characteristics of each translational and rotational DoF of the shank with respect to the thigh. Data of passive elastic knee joint properties were taken from the literature and own measurements.

The elastic moment in flexion/extension direction was modelled by an exponential function of the flexion/extension angle [3]. The proximal-distal displacement was modelled by linear functions, since there was no study available about the elastic characteristics in this DoF.

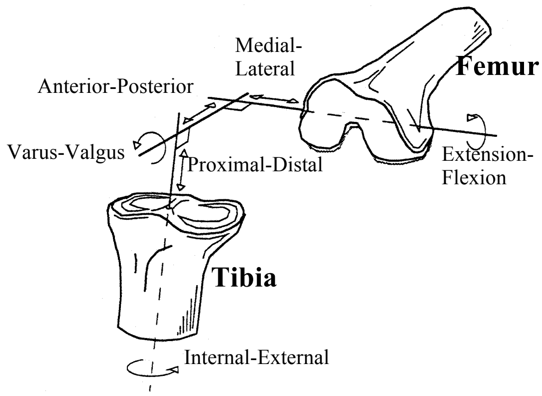

Figure 1: Knee joint rotations and translations (adapted from [5]).

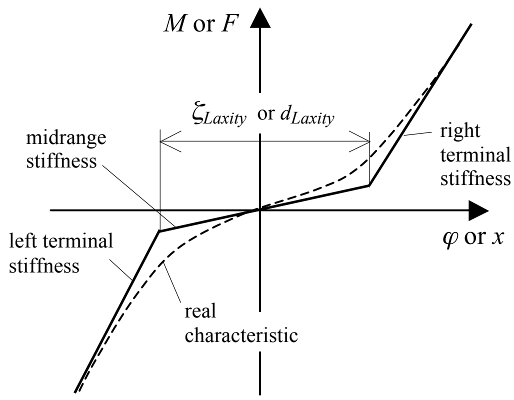

Figure 2: Elastic joint moment or force as function of rotational or translational displacement, respectively.

The joint moments and forces of the remaining DoF (i.e., varus-valgus and internal-external rotation as well as anterior-posterior and medial-lateral displacement) are highly non-linear and depend not only on the rotational and translational displacement, respectively, but also on the flexion angle. Referring to a study of Markolf et al. [1] these elastic joint moments and forces can be divided into three regions: left terminal stiffness, midrange stiffness (laxity area) and right terminal stiffness (Fig. 2). Experimental data [1], [2] were approximated by a piecewise polynomial function. The terminal stiffness areas were fit by linear functions, whereas two cubic functions were applied to describe the midrange stiffness area, one for positive and negative displacement each. The elastic joint moment M_i around an axis i can be described as a function of the respective joint angle φ_i and the flexion angle $\varphi_{flexion}$:

$$M_i(\varphi_i,\varphi_{flexion}) = \begin{cases} (\varphi_i - \varphi_{laxity}(\varphi_{flexion}))\cdot D_{TerminalRight}(\varphi_{flexion}) + \dfrac{\varphi_{laxity}(\varphi_{flexion})}{2} D_{Midrange}(\varphi_{flexion}), & \text{if } \varphi_i > \dfrac{3}{4}\zeta_{laxity}(\varphi_{flexion}) \\ D_{Midrange}(\varphi_{flexion})\cdot\varphi_i + \dfrac{0{,}592593}{\zeta^2_{laxity}}(D_{TerminalRight}(\varphi_{flexion}) - D_{Midrange}(\varphi_{flexion}))\cdot\varphi_i^3, & \text{if } \dfrac{3}{4}\zeta_{laxity}(\varphi_{flexion}) \geq \varphi_i > 0° \\ D_{Midrange}(\varphi_{flexion})\cdot\varphi_i + \dfrac{0{,}592593}{\zeta^2_{laxity}}(D_{TerminalLeft}(\varphi_{flexion}) - D_{Midrange}(\varphi_{flexion}))\cdot\varphi_i^3, & \text{if } 0° \geq \varphi_i > -\dfrac{3}{4}\zeta_{laxity}(\varphi_{flexion}) \\ (\varphi_i + \varphi_{laxity}(\varphi_{flexion}))\cdot D_{TerminalLeft}(\varphi_{flexion}) - \dfrac{\varphi_{laxity}(\varphi_{flexion})}{2} D_{Midrange}(\varphi_{flexion}) & \text{if } \varphi_i \leq \dfrac{3}{4}\zeta_{laxity}(\varphi_{flexion}) \end{cases}$$

These four functions were characterised by the four parameter functions: laxity range ζ_{Laxity} (see Fig. 2), and the stiffness values $D_{Midrange}$, $D_{TerminalLeft}$, $D_{TerminalRight}$ of the midrange, left terminal, and right terminal areas, respectively. In these parameter functions the dependency on the knee flexion angle could be expressed by polynomial and hyperbolic functions. A least square algorithm, a gradient descend method and trial-and-error tests were applied to adapt all parameters so that simulated and experimental characteristics agreed well. The four parameter functions for the varus-valgus direction are:

$\zeta_{Laxity}(\varphi_{flexion})$ = 2.943 + 0.0896$\varphi_{flexion}$ -0.0003757 $\varphi_{flexion}^2$
$D_{Midrange}(\varphi_{flexion})$ = 0.7 + 10.3/($\varphi_{flexion}$ +1)
$D_{TerminalLeft}(\varphi_{flexion})$ = 13.3
$D_{TerminalRight}(\varphi_{flexion})$ = 16.056-0.0711$\varphi_{flexion}$+0.00019$\varphi_{flexion}^2$

To apply the above-mentioned equations also to elastic forces, the moment M_i, displacement φ_i, and laxity ζ_{Laxity} have to be replaced by F_i, x_i and d_{Laxity}, respectively.

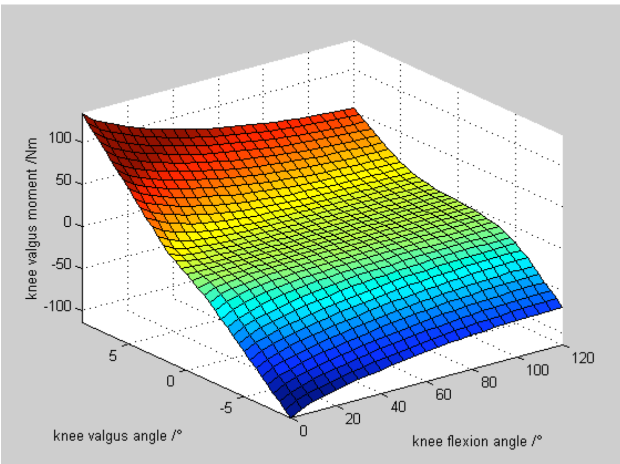

Figure 3: Characteristic of the knee valgus moment as function the valgus and flexion angle.

Results and Discussion

Fig. 3 shows the passive elastic valgus moment as function of valgus and flexion angle. At full extension ($\varphi_{flexion}$ = 0°) the valgus moment depicts a stronger stiffness behaviour than at knee flexion. This corresponds with the qualitative observation that the knee has its maximum stability at full knee extension, when knee ligaments and capsule are under tension. In contrast, at knee flexion there is a large laxity area with a relatively low stiffness.

A similar elastic behaviour can be observed for movements in anterior direction at flexion angles less than 60 ° (Fig. 4).

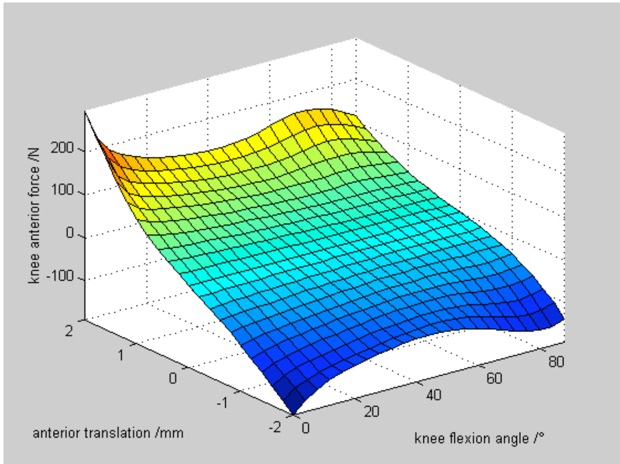

Figure 4: Characteristic of the knee anterior force as function of anterior displacement and flexion angle.

The presented computational model yields realistic knee joint behaviour when applying it in the Virtual Orthopaedic Trainer. Furthermore, the black-box approach allows fast model computations, which is important in order to provide a high-fidelity haptic feedback to the user. In the future, also pathological joint characteristics can be easily described and implemented on the basis of the presented model. In a final step the Virtual Orthopaedic Trainer has to be verified by experienced physicians before it can be applied to medical training.

References

[1] Markolf, K. L., Mensch, J. S., Amstutz, H. C. (1976) Stiffness and laxity of the knee – the contributions of the supporting structures. J. Bone Joint Surg [Am] 58, pp. 583-594.

[2] Piziali, R. L., Rastegar, J., Nagel, D. A., Schurman, D. J. (1980) The contribution of the cruciate ligaments to the load displacement characteristic of the human knee joint. J. Biomech. Eng. 102, 277-283.

[3] Riener, R., Edrich, T. (1999) Identification of passive elastic joint moments in the lower extremities. J. Biomechanics 32, pp. 539-544.

[4] Riener, R., Hoogen, J., Schmidt, G., Buss, M., Burgkart, R. (2000) Knee joint simulator based on haptic, visual, and acoustic feedback, 1st IFAC Conf. on Mechatronics, in press.

[5] Woo, S. L.-Y., Livesay, G. A., Smith, B. A. (1994) Kinematics. In: Knee Surgery. Fu, Harner, Vince (Eds.). Williams and Wilkins, Baltimore, pp. 173-187.