Validation of a three-dimensional model of the knee

Citation for published version (APA):

DOI:
10.1016/0021-9290(95)00149-2

Document status and date:
Published: 01/01/1996

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 14. Jul. 2019
VALIDATION OF A THREE-DIMENSIONAL MODEL OF THE KNEE

L. Blankevoort and R. Huiskes
Biomechanics Section, Institute of Orthopaedics, University of Nijmegen, Nijmegen, The Netherlands

Abstract—Three-dimensional mathematical models of the tibio-femoral joint require input of the geometry of articulating surfaces and ligament insertions, and the mechanical properties of cartilage and ligaments. This paper describes a validation of a knee model through a direct specimen-related comparison between the knee model and the kinematics of four knee joint specimens from which the geometry data were used as input of the model. The knee model is quasi-static and is based on equilibrium of forces and moments. The stiffness properties of the ligaments and articular cartilage were estimated on the basis of data reported in the literature. The so-called reference strains in the ligament bundles for the joint in extension, were determined by using an optimization procedure, minimizing the difference between the kinematics of the model and the kinematics of experimentally obtained flexion motions with an internally or an externally rotated tibia (±3 Nm load). A reasonable to good agreement between the model and the experimental kinematics could be obtained for internal-external rotation laxity tests and varus-valgus rotation. The disparity between the model and the experimental kinematics varied from knee to knee, average deviations ranging from close to zero to 8° internal rotation deviation and from 5 mm posterior to 3 mm anterior position deviation. The average anterior-posterior laxities at both 20° and 90° flexion were within the variations reported in the literature, although for each individual joint with some underestimation or overestimation. It was concluded that the optimization procedure compensated for the lack of menisci and capsular structures by higher prestrains, thereby overestimating the ligament forces. Despite the gross simplifications relative to the complex anatomy of the knee, the present knee model can realistically simulate the passive motion characteristics of the human knee joint. Copyright © 1996 Elsevier Science Ltd.

Keywords: Knee joint, Joint modeling, Joint laxity.

INTRODUCTION

A mathematical model of the tibio-femoral joint can be a versatile tool for parametric analyses of knee ligament function (Blankevoort and Huiskes, 1989) and ligament reconstruction procedures (Bach et al., 1992, Gibou et al., 1986). Three-dimensional knee joint models require the geometry of the articular surfaces and the insertion sites of the ligaments, and the mechanical properties of ligaments and cartilage surfaces (Andriacchi et al., 1983; Essinger et al., 1989; Wismans et al., 1980). The geometry of the articular surfaces and the ligament insertion sites of one or more individual joints were usually measured accurately (Essinger et al., 1989; Wismans et al., 1980), whereas the stiffness parameters for the ligaments and articular contact were based on data reported in the literature (Andriacchi et al., 1983; Essinger et al., 1989; Gibou et al., 1986). Sufficient data are available for the nonlinear stress-strain or force-length relationships of the ligaments (e.g. Butler et al., 1986; Trent et al., 1976) but for the reference strain, i.e. the strain in ligaments for the joint in extension (Wismans et al., 1980), and the related zero-load length of the ligaments there are no data available. In knee models, the ligament reference strains were merely estimated, and sometimes adapted by means of trial and error in order to get a better agreement with experimental data (Blankevoort et al., 1991) or to prevent the ligaments from being overstrained for particular joint motions (Essinger et al., 1988; Wismans et al., 1980).

This study addressed the question how closely a mathematical knee model can approach experimentally obtained passive motion characteristics of a particular knee joint from which the geometry data are used as input. Because the stiffness properties of the articulating surfaces have a small effect on the model characteristics (Blankevoort et al., 1991) and good estimates of the ligament stiffnesses were available, this study was focussed on the unknown parameters, i.e. the reference strains of the ligaments. The ligament reference strains were determined in an optimization procedure based on the minimization of the disparity between the kinematics of the model and those experimentally obtained for a particular knee, for given values of the ligament stiffnesses. After the optimization procedure, the optimized model was then used to stimulate anterior-posterior and varus-valgus laxity tests and the results were compared with data from the literature.

METHODS

The three-dimensional mathematical knee-joint model used in this study, featured anatomically shaped three-dimensional articular surfaces with a thin layer of deformable cartilage and an arbitrary number of nonlinear elastic line elements representing the ligaments. Friction at the articular contact was neglected. The model solved the equilibrium equations of forces and moments from the externally applied loads, the ligament forces, the contact forces and the constraint loads. The constraint forces and moments reacted to the prescribed degrees of freedom. The model accounted for the interaction between the medial collateral ligament and the medial bony edge of the tibia (Blankevoort and Huiskes, 1991). The menisci were not accounted for in the model. Details on the mathematics of the knee model which are...
not given below can be found in Blankevoort et al. (1991b) and Blankevoort and Huiskes (1991).

The femur was assumed to move relative to the tibia. The displacements were expressed as the translations of the origin of the femoral coordinate system, which was located 15 mm proximal relative to the posterior insertion site of the anterior cruciate ligament on the tibia when the joint was extended (Blankevoort et al., 1988). The rotation convention was similar to the one proposed by Grood and Suntay (1983) in the sense that joint rotations were expressed as rotations of the tibia relative to the femur.

Each ligament was represented by multiple line elements connecting the femur and the tibia. The magnitude of the ligament force \( f \) in a line element was related to the ligament strain \( \varepsilon \) by (Wismans, 1980):

\[
\begin{align*}
f(\varepsilon) &= \frac{1}{k} \frac{k}{\varepsilon_1} \varepsilon^2, & \text{when } 0 \leq \varepsilon \leq 2\varepsilon_1, \\
f(\varepsilon) &= k (\varepsilon - \varepsilon_1), & \text{when } \varepsilon > 2\varepsilon_1, \\
f(\varepsilon) &= 0 & \text{when } \varepsilon < 0,
\end{align*}
\]

where \( \varepsilon_1 \) is a strain constant and \( k \) is a stiffness constant. The actual strain \( \varepsilon \) was determined from the actual length \( L \) of the line element and its zero-load length \( L_0 \), by

\[
\varepsilon = \frac{L - L_0}{L_0}.
\]

The actual length \( L \) followed directly from the translations and displacements of the reference strains in the ligaments. The minimization of the ligament forces was performed through a modification of the Levenberg-Marquardt algorithm by using the general least-squares solver LMDIF (from MINPACK (More et al., 1980), Argonne National Laboratory, Argonne, Illinois, U.S.A.). A limit of 0.1 was set to the reference strain \( \varepsilon \), in order to prevent the occurrence of unrealistic reference strains.

---

### Table 1. The ligament parameters in the knee model

<table>
<thead>
<tr>
<th>Ligament Bundle</th>
<th>Knee Specimen</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ligament</td>
<td>( k ) (N)</td>
<td>( \varepsilon_0 )</td>
<td>( \varepsilon_{opt} )</td>
<td>( \varepsilon_{opt} )</td>
<td>( \varepsilon_{opt} )</td>
</tr>
<tr>
<td>Anterior</td>
<td>( a ) 5000</td>
<td>0.015</td>
<td>-0.004</td>
<td>0.067</td>
<td>-0.006</td>
</tr>
<tr>
<td>Cruciate</td>
<td>( p ) 5000</td>
<td>-0.061</td>
<td>0.003</td>
<td>0.100</td>
<td>0.007</td>
</tr>
<tr>
<td>Posterior</td>
<td>( a ) 9000</td>
<td>-0.053</td>
<td>-0.211</td>
<td>-0.230</td>
<td>-0.248</td>
</tr>
<tr>
<td>Cruciate</td>
<td>( p ) 9000</td>
<td>-0.023</td>
<td>-0.249*</td>
<td>-0.024</td>
<td>0.009</td>
</tr>
<tr>
<td>Lateral</td>
<td>( a ) 2000</td>
<td>0.080</td>
<td>-0.004</td>
<td>-0.263</td>
<td>-0.217</td>
</tr>
<tr>
<td>Collateral</td>
<td>( s ) 2000</td>
<td>-0.059</td>
<td>-0.131</td>
<td>-0.059</td>
<td>-0.061</td>
</tr>
<tr>
<td>Collateral</td>
<td>( p ) 2000</td>
<td>-0.040*</td>
<td>0.064</td>
<td>0.100</td>
<td>0.076</td>
</tr>
<tr>
<td>Medial</td>
<td>( a ) 2750</td>
<td>-0.113*</td>
<td>-0.029</td>
<td>0.024</td>
<td>-0.076</td>
</tr>
<tr>
<td>Medial</td>
<td>( i ) 2750</td>
<td>0.070</td>
<td>0.100</td>
<td>-0.024</td>
<td>0.100</td>
</tr>
<tr>
<td>Medial</td>
<td>( p ) 2750</td>
<td>-0.008</td>
<td>0.050</td>
<td>-0.150*</td>
<td>0.051</td>
</tr>
<tr>
<td>Capsule</td>
<td>( p ) 1000</td>
<td>-0.203</td>
<td>-0.115</td>
<td>-0.144</td>
<td>-0.161</td>
</tr>
</tbody>
</table>

\( k \) is the linear stiffness and \( \varepsilon_0 \) is the reference strain. \( \varepsilon_{opt} \) is given for all four knees after the optimization (opt.) procedure to match the models of the four knee joints with internal-external rotation only (int/ext.) and to both internal-external rotation and anterior-posterior translation (int/ext., ant/post.) for flexion motions along the envelope of passive knee motion. Ligament bundles which are slack for both the internal and external motion pathways are marked with *.

(Bundle identifications: \( a = \) anterior, \( p = \) posterior, \( s = \) superior, \( i = \) inferior.)
The motions simulated in the optimization procedures were flexion along the envelope of passive motion (Blankevoort et al., 1988). These flexion motions were defined by two loading conditions, the first with an internally applied axial torque ($M_x$) of 3 Nm and the second with an externally applied torque ($M_x$) of 3 Nm, in absence of other external loads. The axial torque was applied about the long axis ($x_1$) of the tibia, independent of the femoral motions. The choice for these motion pathways was based on the rationale that a limited number of experimental positions were required for the optimization procedure (limitation of computing time) and that all ligaments needed to be strained at least once. The I–E rotations and A–P translations for these two motion pathways, each simulated by 7 joint positions, defined the goal of the optimization procedure. For each model two optimizations were performed. In the first optimization the goal parameter was I–E rotation as functions of flexion only, while in the second optimization the goal parameters were both I–E rotation and A–P translation as functions of flexion. Because the values of the I–E rotation as expressed in degrees were generally higher than those of the A–P translation expressed in mm, a weight factor of 3 was used for the A–P translation.

The final analysis concerned a comparison of the laxity characteristics of the optimized knee models with data reported in the literature. For this purpose the A–P laxity at ±100 N at 20° and 90° flexion and the V–V laxity data at ±20 Nm at extension and 20° flexion were chosen from the *in vitro* and *in vivo* studies of Markolf et al. (1976, 1978, 1984). These studies were consistent and considered representative of other knee laxity studies (Hirokawa, 1993). Each model was used to simulate the A–P laxity tests and the V–V laxity tests while the flexion angle and the I–E rotation were constrained.

**RESULTS**

As illustrated for one knee specimen (Fig. 2), the similarity between the model and the experimental data was not very close. A considerable improvement of the I–E rotations was obtained after optimization of the I–E rotation only at the cost of an
anterior deviation for the internal motion pathway exceeding 4 mm at one point. Optimization of both the I-E rotation and A-P translation brought the A-P translation of the model within 1 mm of the experimental data with a slight increase in the I-E rotation deviation.

In the four knee models, the resulting reference strains differed considerably between the two optimization procedures, to I-E only and to both I-E and A-P (Table 1). In some cases, line elements had reference strains that were so low, that they remained slack for both the internal and external motion pathways. These line elements were not required in the knee model to obtain the optimal match with the experimental data in the cases concerned. When starting the optimization procedures with different initial reference strains, the models converged in nearly all situations to the same solution. Only in those cases where the starting values were extremely high or extremely low, did the solutions differ. In these (physically unrealistic) cases, the optimal solution showed less agreement with the experimental values. A reduction of the reference strain limit from 0.1 (10%) to 0.05 (5%) affected the reference strains in the solution only marginally and hardly affected the quality of fit with the experimental data, showing slight increases in the internal or external rotations. The reference strain limit of 0.05 did, however, reduce the strains in those line-elements which originally had reference strains between 0.05 and 0.1.

The optimization procedures brought the motion characteristics of all four knee models closer to those obtained experimentally, as illustrated by the comparison of the mean deviations and the extreme deviations before and after optimization (Fig. 3). For all specimens, the external motion pathway was found to match the experiments the best, whereas the results for the internal motion pathway varied considerably among the four joints. The optimized models of the knee specimen 2 and 3 showed the best results, whereas the model of knee specimen 1 was the worst. The model of specimen 1 optimized with respect to both I-E and A-P showed an increased deviation of internal rotation of more than 10°, with flexion angles higher than 30°. Two of the models of specimen 4, the one before optimization and the one optimized with respect to I-E only, luxated for internal rotation at flexion angles above 70°. A luxation was characterized by one of the condyles sliding off the tibial plateau, which resulted in a mechanically unstable position. In the overall comparison, the data of the internal motion pathway above 70° of flexion was omitted for this specimen. When the model of specimen 4 was optimized with respect to both I-E and A-P, it did not luxate but showed an increased internal rotation relative to the experimental values of the same order of magnitude as found in specimen 1 for the internal motion pathway above 70° flexion.

The other motion components, i.e. varus-valgus (V-V) rotation, medial-lateral (M-L) translation and proximal-distal (P-D) translation, were assumed to be coupled motions. They were hardly affected by the optimization process. The mean deviations for the coupled V-V and M-L motions were the highest for specimen 2, 1.6° varus and 1.5 mm medial, and the
lowest for specimen 2, 0.7° valgus and 0.2 mm anterior. The deviation in the P–D direction was about −2 mm for all models, which means that the femur was about 2 mm closer to the tibia as in the experiment.

The anterior and posterior laxities at a load level of 100 N of the optimized models compare relatively well with the experimental values of Markolf et al. (1976, 1978) (Fig. 4). At 20° flexion, the models optimized with respect to I–E only, compare better with the values of Markolf et al. (1976, 1978) in particular for posterior laxity. At 90° flexion, the difference between the two optimization strategies is small, except for the model of knee specimen 1, which also showed the worst results after optimization to the internal and external motion pathways. The anterior and posterior laxities at 90° flexion of the models of specimens 3 and 4 were low relative to the average experimental data, but taking into account the 95% confidence interval (approximately mean ± two times standard deviation), the values are not unrealistic.

The V–V laxities of the four models at extension and 20° flexion of the four optimized models compare very well with the average data of Markolf et al. (1976, 1978, 1984) (Fig. 5). The magnitudes of the V–V laxities for the models optimized with respect to I–E only were not much different, less than 10% of the magnitudes obtained with the models optimized with respect to both I–E and A–P.

**DISCUSSION**

In this study the geometric data on the ligament insertions and the articular geometry were obtained from each knee specimen of which also the passive motion characteristics were measured. The geometric data were used as input of a three-dimensional mathematical model whereby the motion characteristics were used to determine the ligament reference strains by mathematical optimization of the match between the experiments and the model, for a given set of mechanical properties of the ligaments and the articular cartilage.

The process of determining the reference strains is based on the assumption that, for a given joint position, the sum of the forces in the ligaments and in the articular contacts balance the externally applied loads. The ligament forces were changed by altering the reference strain. For a fixed joint position this is similar, to some extent, to changing the ligament stiffness whereby the load balance is influenced (Blankevoort et al., 1987). The ligament forces, in turn, will affect the contact forces (Blankevoort and Huiskes, 1989). Implicitly, it is assumed that the configuration of multiple line-elements representing the ligaments, is adequate for the function of all capsular and ligamentous structures of the knee. The structures which are loaded in the real knee, but not represented in the model, have to be compensated for by introducing additional loads on the structures which are represented in the model. When there was a redundancy in the ligament configuration within the knee model, some of the line elements were eliminated in the optimization process by adopting a very low reference strain. This points to a weakness of present knee-joint models. The reference strains as determined in the optimization process, do not represent precisely the reference strains in the real joint because of the compensation mechanism. It can be assumed that the reference strains in the model were overestimated, given the fact that an increase of the reference strain will lead to a higher ligament force. Thus also the ligament strains and ligament forces are overestimated in the model. On the other hand, the optimization technique resolves issues bothering one, whether or not a chosen model configuration is valid for simulating the load balance across the knee. The optimization process will not lead to a satisfactory match with the motion characteristics when those structures are discarded, whose function cannot be compensated for by the structures included in the model.

The suitability of the optimization method to determine the best model was clearly illustrated. Of the four knee models in the present study, those of specimens 2 and 3 performed excellently when optimized to both I–E and A–P. The other two showed poor behaviour with respect to internal rotation at the higher flexion angles. The insufficient compensation of the absence of the menisci by the ligaments in the model could well be the reason for this, although the differences between the intact knees
Representing each ligament by only two or three ligaments and disregarding the menisci and most of the capsular structures is a weakness of the present knee models. It may lead to a non-stable knee joint model for certain joint positions and loading conditions. The question then is whether a dissected knee joint, in which only those structures which are also contained in the knee model are left, will be unstable. In the experimental situation, no compensation for the dissected ligamentous structures can be achieved by increasing the initial tensions in the remaining ligaments. The model analyses do show that the compensation mechanism may not always lead to satisfactory results.

The comparison with the anterior and posterior laxity data of Markolf et al. (1976, 1978), showed that for nearly all optimized models the anterior laxities were realitic for 20 and 90° flexion. The posterior laxity value at 20° flexion seemed to be overestimated in the models which are optimized to both I-E and A-P. It must be noted here that during the optimization process the A-P position of the femur relative to the tibia was optimized and not the A-P laxity. At 90° flexion some overconstraint was present in two of the four models. It was concluded that when forcing the knee model to a correct A-P position, the posterior laxity was affected unfavorably. This was due to the simplified two-line model of the posterior cruciate ligament. Such a discretization of the posterior cruciate ligament may have had a considerable effect on the posterior laxity when omitting a possibly important load-bearing part of the ligament which is located in between the most anterolateral and most posteromedial bundles. In the knee models optimized to both I-E and A-P, the posteromedial part of the posterior cruciate ligament is taut only near extension while the anterolateral part becomes taut for the higher flexion angles. Both bundles are slack and thus not functional at 20° flexion where an intermediate bundle, not included in the model, may have been functional. This problem does not occur with the anterior cruciate ligament because its anterior bundle should remain taut throughout the whole flexion range.

The lateral and medial collateral ligaments functioned sufficiently to restrain external moments and varus-valgus moments. The external rotation as functions of flexion were close to the experimental values and the varus-valgus laxity data were close to the experimental findings of Markolf et al. (1976, 1978, 1984). Here the lack of capsular structures and menisci were well compensated for.

The optimization technique proved to be a powerful tool in optimizing the motion characteristics of the knee model relative to the corresponding experimental data when the values of one or more of the parameters of the model are unknown or of an uncertain nature. It provided an excellent guide for future enhancements of the knee model and the subsequent validations. Similar to other previously reported models (Andriacchi et al., 1983; Essinger et al., 1989; Wismans et al., 1980), the knee model in the present study was of a crude nature relative to the complex anatomy of the knee, e.g., the line element representation of the ligaments and the absence of some of the capsular structures and absence of the menisci. However, an optimized knee model did simulate the passive motion characteristics of the knee more realistically than a nonoptimized knee model. In particular, the simulation of the force balance across the knee can give valuable information on the function and the functional mechanisms of the supporting structures.

Acknowledgements.—This research program was sponsored in part by Grant 90-90 from the Netherlands Organization for Research (NWO/MEDIGON).

REFERENCES


