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Short Communication

A Mechanism for Rotation Restraints in the Knee Joint

L. Blankevoort and R. Huiskes

Biomechanics Section, Institute of Orthopaedics, University of Nijmegen, Nijmegen, The Netherlands

Summary: Ligament function in restraining axial rotation of the tibia relative to the femur cannot be revealed by analysis of ligament forces alone. The action of the articular surfaces should be taken into account as well. In this study, three-dimensional mathematical models of four human knee joints were used to determine the limits of axial rotation between 0 and 90° of flexion, whereby the forces in the ligaments and articular contact were calculated, together with their contribution to the restraint moment that was required to counterbalance the applied axial moment of 3 Nm. In external rotation, the direct axial restraint was provided by the collateral ligaments. In internal rotation, when the cruciate ligaments and medial collateral ligament were predominantly loaded, the direct restraint moment resulting from the ligament forces was not sufficient to counterbalance the applied moment. The articular contact forces, which resulted from balancing the axial components of the ligament forces, contributed considerably to the restraint of internal rotation. Depending on the flexion angle, the contact forces provided approximately 50-85% of the internal restraint, whereas 95-100% of the external rotation restraint was accounted for by the ligament forces.

Understanding ligament function in the knee joint is important in diagnostic and surgical procedures for knee ligament injuries. Most contemporary information on functions of the knee ligaments is derived from experiments. Recent studies were aimed at measuring ligament forces for various motions and loading conditions (1,2,14,15). Directly measured ligament forces give insight into the contribution of the ligaments in balancing the externally applied loads. However, knowledge of the magnitudes of the ligament forces alone is not sufficient. The orientations and locations of those forces should be taken into account as well.

Not only the ligament forces, but also the contact forces at the articular contacts, play a role in balancing external loads. With axial rotation, the intercondylar eminence could also be engaged in restraining axial rotation (9), a mechanism that has not been demonstrated as yet. The purpose of this study was to examine the hypothesis that the restraining mechanism for axial rotation is based on both ligamentous and contact restraints. Because simultaneous measurement of the magnitudes and directions of the ligament tensions and the contact pressures in one experiment is very complex, three-dimensional mathematical mod-

els of the knee (5,7) were used to analyze the functions of the ligaments and the articular contacts in restraining axial rotation in the knee.

METHODS

The three-dimensional mathematical knee joint model as used in the present study and its validation were previously described (5,7,8). The model features anatomically shaped three-dimensional articular surfaces with a thin layer of deformable cartilage and an arbitrary number of nonlinearly elastic line elements representing the ligaments. Friction at the articular contact is neglected. Although the menisci do have a certain role in determining the motion limits of the knee (13), they are not accounted for in the model. The contribution of the menisci to the axial rotation restraints was considered to be small in axial rotation tests under moderate loading conditions (3).

With a given combination of external loads and kinematic constraints, the model was used to calculate the joint position for which there was equilibrium between the external and internal forces and moments (7). The internal forces and moments arose from the forces in the ligaments and articular contacts. In this study, only an internal or external axial moment was applied. The moment was considered to be constant, whereas the forces and moments resulting from the ligaments, articular contacts, and kinematic restraints were functions of the translations and rotations.

Four models were generated on the basis of geometric data from four knees that had been used for extensive experimental evaluations of their passive motion characteristics (4). The surface shapes of the femoral and tibial condyles were measured with a stereophotogrammetric method (11,16) and were represented in the model by spatial polynomial functions. The locations of the ligament insertions in each knee were obtained by roentgen stereophotogrammetric analysis (17). The anterior and posterior cruciate ligaments were described by two line elements each; the
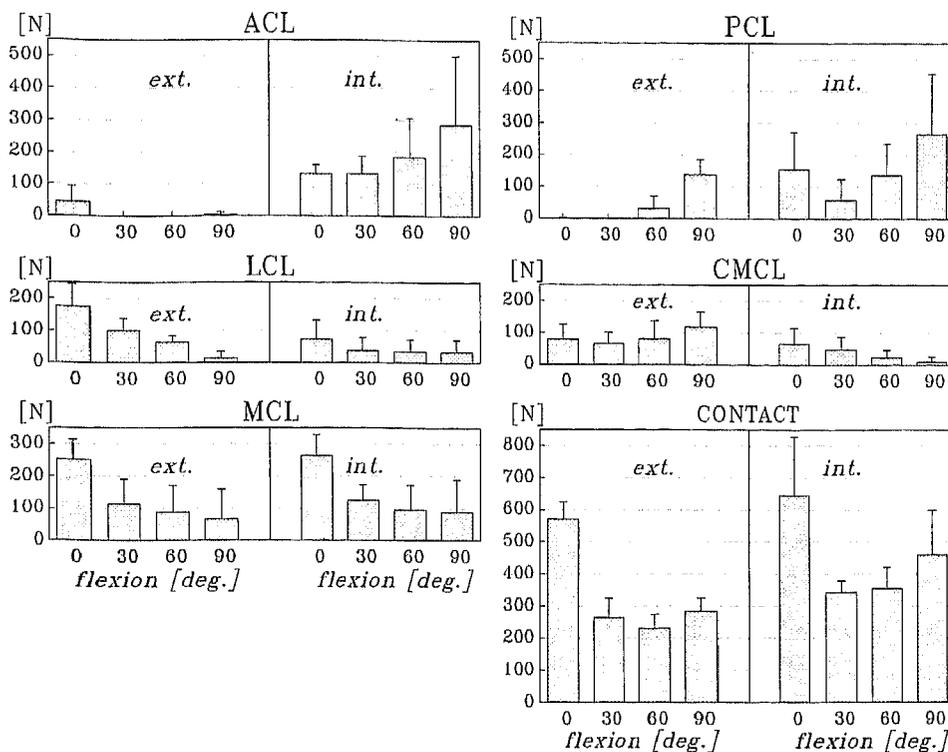
FIG. 1. The average ligament and contact forces for an internal or an external moment of 3 Nm at extension and at 30, 60, and 90° of flexion, as simulated in the four anatomically different knee joint models. Error bars represent 1 SD. ACL = anterior cruciate ligament, PCL = posterior cruciate ligament, LCL = lateral collateral ligament, CMCL = capsular fibers of the medial collateral ligament, MCL = medial collateral ligament.

lateral and medial collateral ligaments, by three line elements each; and the deep, more or less capsular fibers of the medial collateral ligament, by two line elements (6). All line elements ran in straight lines between the femoral and tibial insertions except the medial collateral ligament, which was bent in its course by the medial osseous edge of the tibia. Each model was validated on the basis of a subset of the experimental data, i.e., the internal and external rotation limits as functions of flexion with a 3 Nm moment, whereby the zero-load length of the ligament bundles was optimized to obtain the best fit with the experimental data (8).

In each of the four knee joint models, internal-external rotation was simulated with the knee in extension and at 30, 60, and 90° of flexion. At each position, an internally or externally directed axial moment of 3 Nm was applied, whereby only the prescribed flexion angle was constrained and the remaining five degrees of freedom of motion were unconstrained. No other forces or moments were applied to the knee model in the two axial rotation tests. It should be emphasized that the test simulated in the knee model was not a test with one degree of freedom of motion. The location of the internal-external rotation axis was not fixed, because the remaining degrees of freedom of motion determine the location of the axis in an axial rotation test. Resulting from the model simulations were the forces in the ligament bundles and the articular contacts, and their contributions to the restraint required to counterbalance the constant axial moment of 3 Nm. Although the model provided the forces of the separate bundles of each ligament, for the analyses the total ligament force was calculated by summing the bundle forces. The total joint contact force was determined by summing the medial and lateral contact forces.

Two-way analysis of variance for repeated measures was used to test the significance of the effects of flexion and axial rotation on the ligament forces, contact forces, and restraining moments, at an α level of 0.05. A Student-Newman-Keuls test was used for multiple comparisons between flexion angles at an α level of 0.05.

RESULTS

The average ligament and contact forces in the four knee models at extension and 30, 60, and 90° of flexion (Fig. 1) showed that the anterior cruciate ligament was tensioned mainly by an internal rotation moment (statistically significant, $p < 0.05$). There was no significant effect of the flexion angle. The difference between internal and external rotation for loading of the posterior cruciate ligament was not significant; there was only a significant effect of the flexion angle in the sense that the load at 90° was significantly greater than at the other flexion angles. The lateral collateral ligament acted mainly to restrain external rotation (significant), and its load was significantly greater at extension than at the other flexion angles. The load of the medial collateral ligament was significantly affected only by flexion; the load was greater at extension than at the other flexion angles. The medial collateral ligament was loaded equally in internal and external rotation. For the capsular fibers of the medial collateral ligament, there was a statistically significant interaction between the effects of flexion and rotation, which was caused by the opposite behavior of the ligament force between internal and external rotation as functions of flexion. The summed contact forces showed no significant differences between internal and external rotation, but they were greater at extension than at the other flexion angles.
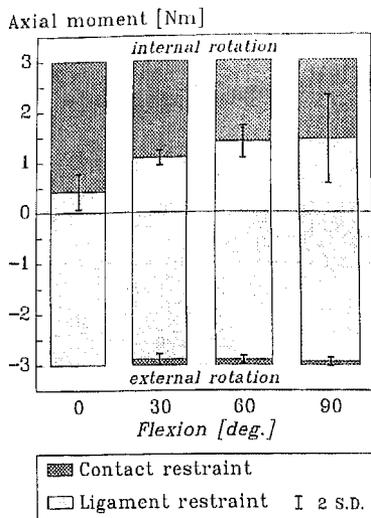
Axial moment [Nm]

FIG. 2. The average distribution of the axial moments over the ligament restraint and the contact restraint with the knee at extension and at 30, 60, and 90° of flexion, as simulated in the four anatomically different knee joint models. Error bars represent 2 SD.

The contributions of the ligament and contact forces to the total axial moment as functions of flexion (Fig. 2) were significantly affected by axial rotation. Internal rotation showed a significantly greater contribution of the contact forces to the rotation restraint than did external rotation. For both internal and external rotation there was a significant flexion effect; the relative contributions were different for extension and the other flexion angles. In the four models, the relative contributions of the contact forces to the rotation restraint were relatively high at 90° of flexion, ranging from 18 to 73%.

DISCUSSION

Previously, studies of ligament function were aimed only at investigating the contributions of the ligaments to motion restraints without quantifying the effects of the restraint provided by the articulating surfaces. As was previously demonstrated in a single knee joint model at 20° of flexion, the restraint mechanism for internal-external rotation is a concerted action of the ligaments and the articular surfaces (12). In a general sense, when the tibia was moved toward internal rotation, the forces in the medial collateral ligament and the cruciate ligaments increased, whereas the forces in the lateral collateral ligament and the capsular fibers of the medial collateral ligament decreased. Due to the oblique orientations of the cruciate ligaments and medial collateral ligament relative to the tibial axis, their force components in the horizontal plane acted directly to restrain internal rotation. However, the ligament forces contributed only partially to the axial moment required with internal rotation. The contact forces also contributed to the restraint of internal rotation because of the relative orientation of the me-

dial and lateral tibial surfaces. If projected in the frontal plane, the medial and lateral tibial surfaces are oblique relative to each other. If projected in the sagittal plane, the medial surface has a greater posterior slope than the lateral surface. Because of this relative inclination of the medial and lateral tibial surfaces, an axial translation was coupled to the axial rotation, whereby the tibial and femoral insertions of the ligaments moved farther apart. This resulted in additional tensioning of the ligaments. The contact forces, in their turn, had an oblique orientation relative to the tibial axis. Their components in the horizontal plane contributed additionally to the internal rotation restraint (12). Since no compressive loads were applied to the joint, the articular contact forces resulted from balancing the axial components of the ligament forces.

Although the statistical power of the study was low and not all effects of rotation and flexion were shown to be significant, the restraining mechanism described above for one joint model was demonstrated in this study in four anatomically different models of the knee for the range between extension and 90° of flexion. The presence of a restraint of articular rotation was hypothesized by Goodfellow and O'Connor (9) for both internal and external rotation. From experiments in which the tensions in the four ligaments of the knee joint were measured, Ahmed et al. (1) concluded that an additional, unknown restraint must assist the ligament forces in restraining internal rotation. The present analysis partly confirmed (internal rotation) and partly rejected (external rotation) the hypothesis of Goodfellow and O'Connor, and it revealed the additional restraining mechanism anticipated by Ahmed et al. (1,2).

The way the ligament parameters were selected for the knee models was described previously (6). It was assumed that the geometric data from the four joints were accurate. Furthermore, it was shown that the model was not very sensitive to the geometric and material parameters describing the deformable contact between the tibia and the femur (7). The stiffness properties of the ligament were obtained from data in the literature. By varying the resting lengths of the line elements, the internal and external rotation limits of the knee models were made to match the experimental data for a given set of stiffness parameters (8). In this process of optimization, the forces in the ligaments were adapted such that the internal forces of ligaments and contacts balanced the applied axial moment. This means that the forces in those structures that were present in the experiment but were not accounted for in the model, such as those in the menisci and the capsular structures, had to be compensated for by the forces in the ligaments in order to obtain an optimal force balance. It was concluded that the ligament forces in the knee model were overestimated (8).

The lack of menisci and capsule, together with the overestimation of ligament forces, are limitations of the knee model when the results for the ligament forces are compared with those of previous studies (1,2,14,15,18,19). In a general, qualitative sense, the actions of the ligaments did mimic the behavior of ligaments, as determined by *in vitro* experiments. What could not be demonstrated before in the experimental studies was the interaction between the ligaments and the articular surfaces in restraining internal rotation. Of course, neglecting the menisci and capsular structures in the knee model, which led to the overestimation of the ligament forces with axial rotation, is a shortcoming of the model, but the geometric relationship between the ligament insertions and articulating surfaces will result in the mechanical interaction described here.

The consequences of the interaction between the ligaments and the articular contacts in experimental ligament function studies depend on the experimental approach. When ligament forces are measured directly, only the direct contribution of the ligament to the motion restraints can be determined if the three-dimensional positions and orientations of the ligaments are taken into account. The contact restraint remains unknown. Thus, the importance of a particular ligament as a motion restraint may possibly be underestimated because of its interaction with the articular surfaces. When a ligament is cut in a sequential cutting experiment (10), its direct contribution to motion restraints and its indirect contribution through the articular contacts are affected. These two effects cannot be isolated. Because experiments that combine measurements of ligament forces and contact forces in one knee are very complicated, the application of analytical tools such as the three-dimensional knee model is essential in addition to experiments. An important feature of a numerical experiment is that the conditions can be controlled in an ideal manner. In the mathematical knee model, the angles of flexion and axial rotation can be prescribed while the remaining four degrees of freedom of motion are unconstrained and, except for the constraint moments that maintain the prescribed rotations, the joint is truly unloaded. Such conditions are difficult to realize in experiments using real knee specimens. This should be carefully considered in the design stage of such experiments.

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