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Influence of Soft Structures on Patellar Three-Dimensional Tracking

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During knee flexion, the human patella moves along a complex path resulting from the combined actions of articular contact and soft-tissue stabilization. The current study is an attempt to characterize the role of these soft structures on patellar kinematics. To this end, the three-dimensional patellar motion during full knee flexion was accurately measured before and after partial dissection of the joint. The guiding role of the femoral groove prevailed over soft-tissue action through most of the range of motion. At full extension, however, when the patella and the femur were not in contact, the influence of the retinaculi was most noticeable, highlighting the unstable behavior of the patella near extension. The differences between the intact and dissected knee kinematics suggested that control over patellar motion is ensured by the transverse soft-tissue structures near extension and by the patellofemoral joint geometry during further flexion.

Patellar disorders, including anterior knee pain syndrome and instabilities, presumably relate to abnormalities of the extensor apparatus with respect to mechanical or anatomic factors. It has been suggested that an abnormal tracking of the patella on the femoral groove would induce changes of patellofemoral pressure patterns with repercussions on cartilage and subchondral bone stress distributions.[1,5,7] This hypothesis has justified most of the studies dealing with measurements of the three-dimensional tracking of the patella[1,12,14,16] or corresponding contact patterns.[4,6,9] Van Kampen and Huiskes[15] have mentioned that currently available data describing the three-dimensional tracking of the patella lack consistency and proposed a standard and accurate experimental setup for measuring three-dimensional patellar kinematics.[14]

A further step necessary to understand the relationship between kinematics and patellar stress distribution is to characterize the extensor mechanisms by means of biomechanical hypotheses. The current experimental study intended to provide a simplified anatomic description of the extensor mechanism and to measure the influence of these simplifications on the patellar three-dimensional kinematics. This was achieved by comparing the patellar kinematics of a normal intact knee with that of the same joint where only the main elements were left, *i.e.*, both cruciate and both collateral ligaments in the tib-

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iofemoral joint, the patellar tendon in the patellofemoral joint, and the rectus femoris pulling on the proximal part of the patella.

MATERIALS AND METHODS

Knee kinematics were accurately measured by rigorously using the same motion rig and experimental protocol as the one introduced by van Kampen and Huiskes.[15] Two intact right knees, removed from fresh frozen postmortem cadaver legs with no radiologic sign of pathology were used. At the time of measurement, the specimens were brought to room temperature, taking care to keep them moist with a physiologic solution. Intramedullary rods were cemented in the femur and the tibia. Each knee then was mounted in a motion rig (Fig. 1), allowing precise control of the flexion process. The femur was rigidly fixed on the device. The tibia could be flexed along a circular rail. Internal-external and varus-valgus rotations of the tibia were not restrained, allowing natural knee flexion to occur. Internal or external rotations of the tibia could be controlled by applying a corresponding torque about the tibial axis, however. The measured knees were loaded through the four muscle bellies of the quadriceps, using strings sewn on the muscles. Care was taken to ensure that the pulling forces were oriented along each of the four tendons. In the first set of experiments, the joints were left intact and a 20-Newton (N) load was applied on each quadriceps muscle, representing a total applied force of 80 N. Although much lower than physiologic loads on the patella, it was already shown by van Kampen[14] that in such an experimental setup, the loads applied on the quadriceps have a negligible influence on the patellar motion. The knees then were flexed from full extension (0° flexion) to full flexion (150° flexion) by 15° increments. Three such flexions were performed for each knee: a neutral one with no torque applied about the tibial axis, an external one with a −3 Newton-meter (Nm) torque applied about the tibial axis, and an internal one with a +3 Nm torque. In the second phase of the experiment, the knees were partially dissected so that the only links left between the femur and the tibia

FIG. 1. View of the knee testing device. The tibia is flexed around the circular arc while the femur is rigidly fixed on the frame.

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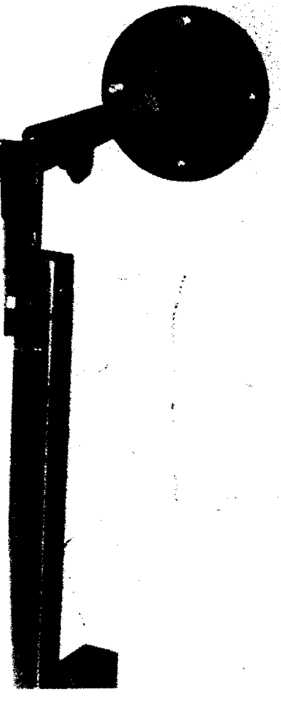

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were both cruciate, both collateral ligaments and the menisci. Both retinaculi were removed and the patella remained attached to the tibia only through the patellar tendon. Proximally, only the rectus was kept for loading the knee with a 40-N load. The three flexions (neutral, external, and internal) were repeated.

All kinematics were measured using the roentgen stereophotogrammetric analysis system developed by Selvik,[13] *i.e.*, by reconstructing the spatial position of radiopaque landmarks using two projections of them. Six tantalum pellets were inserted percutaneously without any dissection in the cortex of each bone. Once the three-dimensional position of the roentgen tube foci and corresponding object image were known, it was possible to compute the three-dimensional position of the original objects (patella, femur, and tibia) with a precision of approximately 50 μm. The femur was fixed, and a laboratory reference system, whose origin was located in the intercondylar notch, was attached to it. Similarly, two body-fixed coordinate frames were attached to the patella (at the center of the anterior patellar surface) and to the tibia (centered on the tibial crest). At each flexion step, the positions of the markers in the tibia and the patella were referred to the fixed reference system. The kinematics of the patella then could be expressed as the set of translations and Eulerian rotations of its attached coordinate frame between the successive flexion increments with a precision of 0.1° on the rotations and of 0.05 mm on the translations. The body fixed reference frames (for the tibia and the patella) and the laboratory fixed reference frame (for the femur) are depicted on Figure 2 with corresponding sign convention.

Each position of the tibia and of the patella referred to the absolute reference frame associated to the femur of the corresponding intact knee at full extension (0° flexion). In such a description, the rotations are order dependent. In this study, knee rotations were carried first around the x-axis then the y-axis and finally the z-axis (called, respectively, flexion, tilt, and rotation axes). Furthermore, patellar shift represented translation along the patellar x-axis. For the tibia, tilt angles corresponded to internal–external rotations and rotation angles corresponded to varus–valgus rotations.

RESULTS

The kinematics of both knees used in the current study compared well with the previously measured results of van Kampen (Fig. 3).[15] The results before and after partial dissection are summarized in Figure 4 for the first knee specimen and in Figure 5 for the second. The small differences between the curves for each knee are related to the inevitable interspecimen anatomic variations.

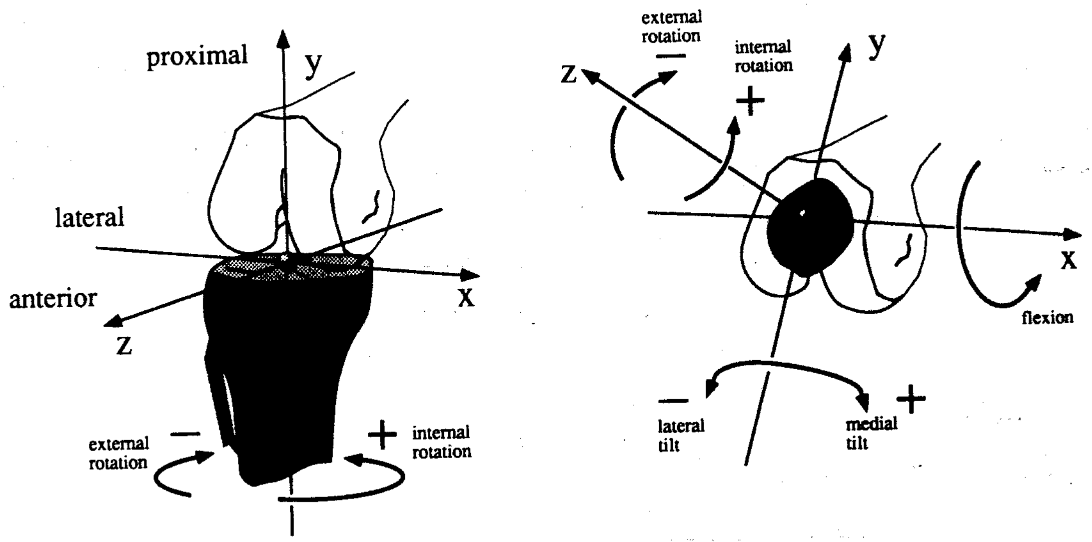


FIG. 2. Reference frames used in the current study to describe tibial and patellar motion. Sign conventions are also represented (internal rotations are positive).

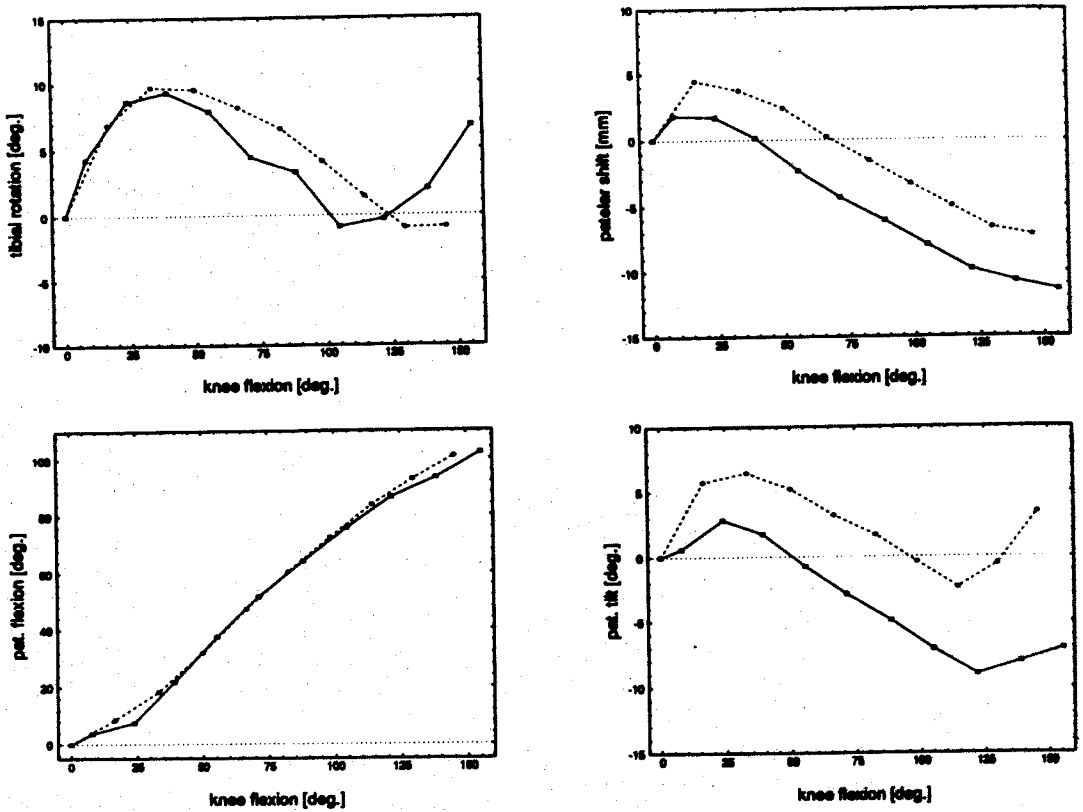


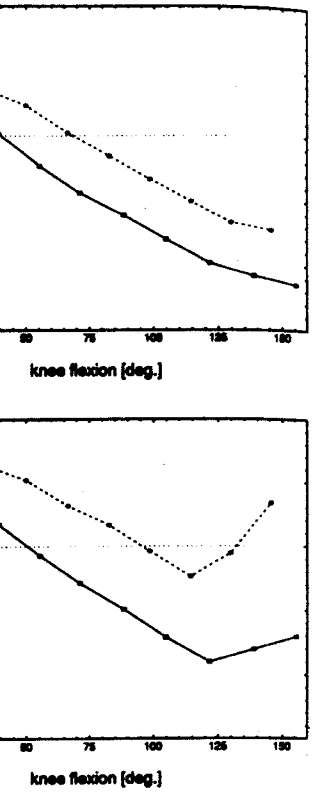
FIG. 3. Comparison between kinematics of current study first knee specimen (solid curve) and van Kampen's fourth knee specimen (doted curve).[14] Top left: tibial rotation. Top right: patellar shift. Bottom left: patellar flexion. Bottom right: patellar tilt. Each kinematic parameter is expressed as a function of knee flexion. Differences between the respective curves indicate inter specimen variations, whereas the global curve shapes indicate very similar trends.

TIBIAL INTERNAL-EXTERNAL ROTATION

Table 1 lists the internal–external tibial rotations achieved by applying the 3-Nm torques about the tibial axis at 0°, 45°, and 90° knee flexion. The tibial neutral pathway showed a screw-home rotation, *i.e.*, an important internal rotation, during the first 15° flexion, as already observed by previous investigators.[2,17] The rotational laxity (under ±3 Nm torques) slightly increased after partial dissection: for the first knee specimen (Fig. 4), the external torque only produced a small additional rotation ($\approx 3°$), whereas the internal torque increased the corresponding rotation by approximately 5°. The second knee specimen (Fig. 5) was more sensitive to dissection, because rotational laxity (internal and external) increased by almost 10° for the same applied torques.

PATELLAR FLEXION

Flexion of the patella, which is the predominant characteristic of patellar motion, followed the tibial flexion but at a lower rate. The ratio between the patellar flexion and the tibial flexion angle was less than unity in all cases. At full knee flexion, the patellar flexion reached 102° for Knee 1 and 98° for Knee 2. Tibial rotation had little influence on patellar flexion. After dissection, flexion was not



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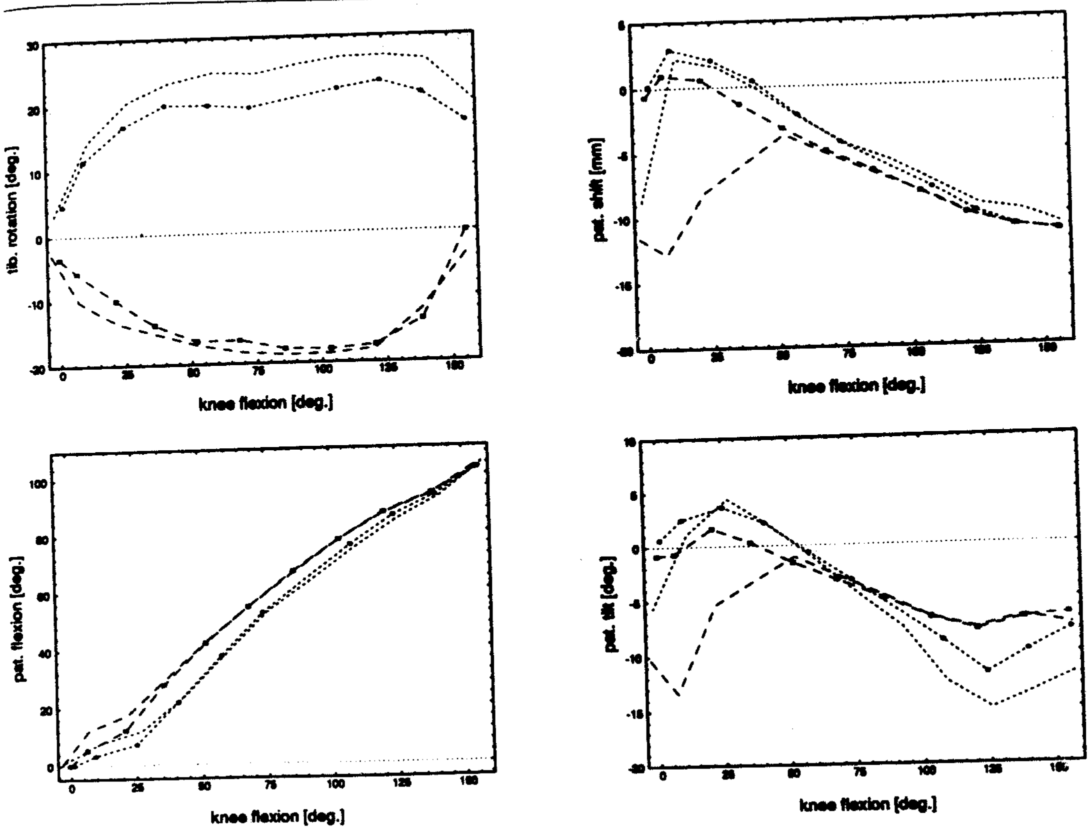


FIG. 4. Kinematic result for the first knee specimen as a function of knee flexion. Top left: tibial rotation. Top right: patellar shift. Bottom left: patellar flexion. Bottom right: patellar tilt. Dotted curves represent knee flexion with internal tibial rotation. Dashed curves represent knee flexion with external tibial rotation. Curves marked with black dots stand for the intact knee. Curves without plotting symbols stand for the dissected knee.

changed significantly, showing the relatively small influence of transverse soft-tissue structures on the patellar sagittal motion.

PATELLAR TILT

Patellar tilt about the y-axis described a wavy pattern: medial during the first 20° flexion (with a maximum medial tilt of 3.2° for the first specimen and of 7.5° for the second specimen at 15° knee flexion), lateral until 100° flexion (with a maximal lateral tilt of −9° for the first knee and of 0.2° for the second one), and medial again in the last phase of flexion. This pattern reflects the profile differences between the lateral and the medial femoral condyles. When the knee was dissected, the only difference in the patellar tilt was an additional lateral tilt of 8° for Knee 1 one (12° for Knee 2) at full extension, which had already disappeared at 15° flexion in the cases of neutral and internal rotations of the tibia. The tilt of the dissected patella was more sensitive to external tibial rotations, however, as shown by the additional 14° lateral tilt for the first knee (21° for the second knee) at 15° flexion, and a standard pattern, which was recovered only at 60° flexion.

PATELLAR SHIFT

The mediolateral translation of the patella was affected by tibial rotations during the

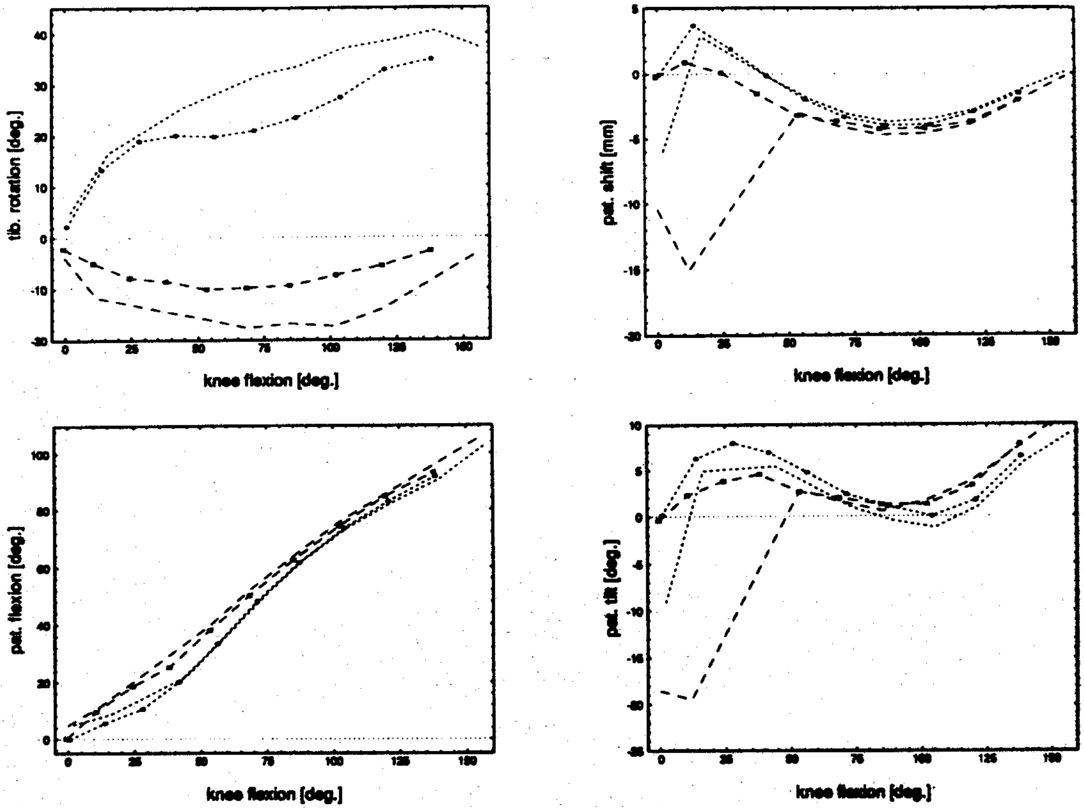
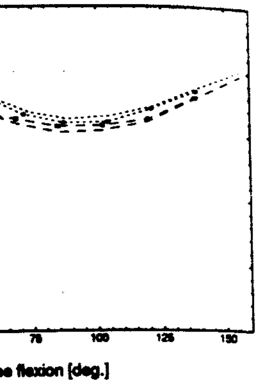


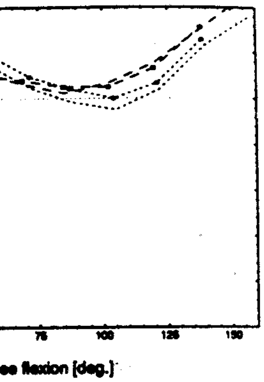
FIG. 5. Kinematics result for the second knee specimen. Same conventions as for Figure 4.

first half of the flexion, with lesser medial shift under external tibial rotation (0.9 mm at 15° knee flexion for both specimens). The effects of dissection on patellar shift were similar to those described for patellar tilt: at full extension, the dissected patella of the first knee had an extra lateral shift of 10 mm (7.5 mm for second specimen). This lateral shift was even more pronounced during flexion under lateral tibial rotation at 15° knee flexion (13 mm for Knee 1 and 16 mm for Knee 2).

TABLE 1. Tibial Rotations (in Degrees) Achieved With an Internal (+3 Nm) or External (−3 Nm) Torque Applied About the Tibial Axis, at 0°, 45°, and 90° Knee Flexion

	Knee Specimen 1				*Knee Specimen 2*			
	Intact		*Dissected*		*Intact*		*Dissected*	
Flexion Angle	*+3Nm*	*−3Nm*	*+3Nm*	*−3Nm*	*+3Nm*	*−3Nm*	*+3Nm*	*−3Nm*
0°	4.5	−3.5	5.1	−4.8	2.2	−2.1	4.9	−4.0
45°	19.8	−13.9	23.2	−17.1	20.0	−8.5	25.5	−13.0
90°	20.1	−17.8	25.8	−18.7	23.5	−9.3	33.6	−16.8





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ee Specimen 2		
	Dissected	
'm	*+3Nm*	*−3Nm*
1	4.9	−4.0
5	25.5	−13.0
3	33.6	−16.8

DISCUSSION

The kinematics of both intact knees measured in the current study presented clear similarities with previous results, thus indicating the existence of specific trends in patellar motion.

Huiskes and Blankevoort[8] illustrated how joint kinematics result from the better combined actions of the joint articular surface geometry and of the soft tissues attached to the joint. The objective of the current study was to assess the specific role of the patellofemoral joint geometry on patellar motion by subtracting the soft-tissue stabilizing effects.

As already noted by van Kampen and Huiskes,[15] tibial rotation plays an important role on patellar kinematics, inducing two possible causes for changes in patellar motion after partial knee dissection: first, the removal of the ligamentous structures attached to the patella will modify proximal transverse force equilibrium and, second, variation of the tibial kinematics after soft-tissue removal will modify the orientation of the patellar tendon pulling force.

During neutral flexion, tibial rotation was not significantly influenced by the removal of the capsule. Applying axial torques on the tibia during flexion generated passive tibial rotation envelopes. The shape differences between these envelopes for intact and partially dissected knees were small, thus highlighting the essential role of the collateral and cruciate ligaments in tibial rotational stability.[3,10,11]

The measured patellar kinematics for the intact specimen were close to previously reported results and could be globally characterized by a progressive patellar flexion, a wavy patellar tilt, and a lateral shift during knee flexion. The effects of removing all the peripatellar soft structures (except the patellar tendon) were analyzed under each knee loading condition: neutral, internal, and external knee flexion.

Significant patellar motion changes were observed during neutral flexion. These changes, however, did not affect every kinematic parameter evenly; patellar flexion remained almost unchanged after partial dissection.

Two kinematic parameters were particularly sensitive to dissection: patellar shift and patellar tilt. Both parameters varied only near extension. The patella shifted laterally approximately 10 mm for both specimens at full extension. This lateral excursion disappeared at 30° flexion, and a normal intact knee pattern for patellar shift was recovered during the rest of the flexion. The result of the pulling forces of the quadriceps tendon and of the patellar tendon draws the patella laterally because of the Q-angle between these pulling forces.[9] From the current results it could be seen that the removal of the medial soft structure strongly accentuated this tendency. Furthermore, when the patella started to be guided in the trochlear groove at flexion angles greater than 30°, patellar shift became identical in both intact and dissected knees.

Patellar tilt presented similar variations after partial dissection: at full extension, both specimen patellas tilted laterally by about 10°. This extra tilt was observed only during the first 30° flexion, leaving patellar tilt unchanged from that of the intact knee at larger flexion angles. From a mechanical point of view, in the absence of any patellofemoral contact or in the case of a small contact area about which the patella could tilt, the extensor mechanism presented instabilities that can be seen on the tilt curves (Figs. 4 and 5). At higher flexion angles, however, the contact between the patella and the femoral trochlea suppressed this instability and imposed a patellar equilibrium position that was no longer influenced by the retinaculi.

Applying an internal torque about the dissected knee tibia produced the same patellar shift and tilt patterns between 0° and 30° flexion as for the neutral dissected case, showing the independence of tibial internal rotation on these parameters in extension. In terms of the passive joint motion envelope, dissecting the knee only slightly widened the internal component of the shift envelope for both specimens. The tilt envelope widened more for the first knee than for the second one at flexion angles greater than 75°, indicating that under internal tibial rotation soft structures could influence patellar tilt over the full range of flexion.

When an external torque was applied about the dissected tibia, changes in patellar motion near extension were more pronounced than in the case of neutral flexion. Until 60° flexion, shift and tilt curves significantly deviated from corresponding curves for intact knee and dissected knee neutral/internal flexions. Both knees showed a pronounced peak of shift and tilt at 15° flexion, suggesting the importance of the medial retinaculum on patellar stabilization under external tibial rotation near extension. At higher flexion angles, however, the external component of passive patellar shift and tilt was not influenced by removal of the retinaculi.

Some remarks should be made in view of the preceding discussion concerning patellar kinematics and the pertinence of a simplified anatomic description for representing the extensor mechanism of the human knee.

Flexion of the patella is a kinematic variable that was never influenced by the presence or absence of transverse soft structures. In this sense, the articular surfaces and the relative orientation of the pulling forces on the patella completely determine this motion parameter. This parameter primarily describes the sagittal component of patellar motion and therefore shows the predominant working mode of the extensor mechanism in the sagittal plane.

During early flexion, when the patella is not seated firmly in the femoral groove, the medial soft structures play a crucial stabilizing role. The patella is then very unstable in tilt and in lateral shift, under the effect of the extensor apparatus forces. The medial retinaculum and the vastus medialis exert important kinematic restraints while the patellofemoral contact area is still small. This stabilizing role is further accentuated with a laterally rotated tibia, clearly demonstrating the importance of these tissues on patellar stability near extension.

The role of the lateral retinaculum did not appear clearly in this study, which confirmed the results of van Kampen,[14] who observed no significant changes in patellar tracking after lateral retinaculum release. It is, however, assertive to neglect its role. From a biomechanical point of view, it most probably equilibrates the stabilizing action of the medial retinaculum when the patella fits into the femoral groove and also stabilizes the patella in its tilt motion.

Within the framework of a highly reproducible experimental setup with a standardized procedure for measuring three-dimensional patellar tracking, it was possible to quantify the stabilizing effects of the retinaculi on patellar motion in terms of kinematic variations. The medial retinaculum and the vastus medialis appeared to be important stabilizing structure near full extension. During further flexion, patellar stability was mainly provided by joint surface congruence.

From a clinical point of view, this study suggests further investigation of the behavior of the patella during the first 30° flexion: similar kinematic studies using smaller flexion steps could provide relevant information on how the patella enters the femoral groove. In this way the role of the retinaculi in guiding the patella to the correct position for smoothly entering on the proximal part of the femoral groove in early flexion might be better understood.

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EDGMENTS

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