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THE MECHANICS OF EXTENSION OF THE KNEE-JOINT

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From a purely mechanical aspect the function of the knee-joint is of great interest since its impairment is a common orthopaedic problem. In a series of studies conducted at the Department of Orthopaedics at Umeå special attention has been devoted to this joint (3-6, 8). The object of the present one has been to examine the movements that occur between the articular surfaces, and the forces involved in active extension of the knee.

MATERIAL

The knee-joints of 15 healthy subjects were examined radiographically and a follow-up of some 30 arthrographic examinations of the knee was performed in order to localize the position and insertion of the anterior cruciate ligament.

METHODS

On the models of the knee obtained from sagittal radiographs of the joint in positions from extension to about 90° flexion ordinary methods of calculation used in mechanics were applied. The film-focus distance was 70 cm and the enlargement factor was 1.08. To facilitate identification of the patellar ligament and the distal part of the anterior cruciate ligament a low-kilovoltage exposure was used.

From the arthrograms it was found that the insertion of the anterior cruciate ligament in the intercondylar groove of the femur was usually half a centimetre from the posterior limit of the groove. The accuracy of this estimate could be checked, it being assessed on the same knee in both extension and 90° flexion. The distance between the two ends of the ligament should be the same, and this was the case within 2-3 mm. With the positions of the two ends of the ligament known, its direction could then be determined.

For each subject the points of contact between the tibia and femur were drawn in for the various positions of the knee-joint examined. In addition the distances between the points of contact were measured on the tibial and femoral articular

surfaces in extension and at different angles of flexion. The radiographic enlargement was compensated for. Six to eight positions of the knee, from extension to about 90° flexion, were examined on 5 subjects, and two or three positions on the others.

MECHANICS OF THE KNEE-JOINT

The movements of the knee-joint are usually regarded as a combination of rocking and gliding, with the first 20° of the flexion a pure rocking movement and the rest a glide (1, 2, 7, 9, 10). These movements, which occur in the sagittal plane, are sometimes accompanied by a simultaneous rotary movement, the terminal stage of which is said to be obligatory. It has been shown by Hallén & Lindahl (5), however, that the terminal rotation is variable and not compulsory. In this study account was taken only of the movement in the sagittal plane. By definition, in a pure rocking movement new points of the two articular surfaces (of the femur and tibia) constantly come into contact with each other in equidistant points. If the points are not equidistant the movement is a combination of a rocking and gliding. Finally, if new points on one surface (the femur) constantly come into contact with the same point on the other surface (the tibia) there is pure slipping.

In active extension of the knee-joint the force exerted by the quadriceps acts *via* the patella, and the ligamentum patellae pulls on the tuberosity of the tibia (X, in Figure 1). Resistance to this movement may occur or be applied at any points on the tibia, but usually it acts peripherally. For instance, in extension of the knee against a resistance with the subject supine the force is usually applied just above the ankle. In this study the forces acting in the knee-joint were calculated on the assumption that the force (R) resisting extension was applied 30 cm distally to the joint space. The same site was used in a simultaneous examination of the maximum force of extension in the sound knee-joint. The forces will depend on the point at which the resisting force is applied.

If a tractive force is applied to the tuberosity of the tibia at the same time as a resisting force 30 cm peripherally on the tibia, the articular surfaces of the tibia and the femur will be pressed together. If the surfaces were congruent this compressive force would be distributed uniformly over them, but otherwise it will act in the line of contact, as in the case of a cylindrical surface in contact with a plane. The force arising between the articular surfaces is usually referred to as the normal force (N) and it acts perpendicular to the tangent at the point

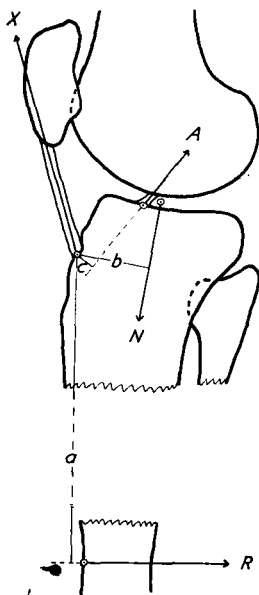


Figure 1. Diagram drawn from a radiograph of the knee-joint showing the forces acting on the tibia in extension. X. Traction of the ligamentum patellae. A. Traction of the anterior cruciate ligament. N. Normal force acting on the tibia at its point of contact with the femur. R. The force with which the distal part of the lower leg, 30 cm below the knee, is pressed forwards in extension.

of contact. As the tibia and femoral condyles are not congruent at any stage of the movement the force will in theory act more or less in a line; but since the cartilage is soft and the menisci occupy part of the space between the incongruent surfaces the force will in practice be distributed over an area about the theoretical line of contact, which in the sagittal plane will be seen as a point. From the mechanical aspect the normal force may be considered to pass through the point of contact between the articular surfaces. When the cartilage is normal and of uniform thickness this is the point at which the distance between the radiographic contours of the articular surfaces is a minimum. At its posterior limit the radius of the femoral condyles is small, and the point is easy to find, but at its anterior limit the radius of the femoral condyle is considerably larger and the point is then more difficult to locate.

The 3 forces under discussion, namely the pull on the tuberosity of the tibia, the force of resistance acting peripherally on the tibia, and the normal force, are not in equilibrium. Moreover, there must be a

force that prevents the tibia from being displaced forwards; this force is most likely to be located in the anterior cruciate ligament (*A*), the prime function of which is to prevent forward displacement of the knee-joint (the "drawer effect" will be positive when the ligament is ruptured). With moderate loads the collateral ligament and capsule will contribute to the stabilization of the joint, but when larger forces are acting it is logical to suppose that the forward force will be taken up largely by the anterior cruciate ligament.

To be able to calculate the relations between the 4 forces (*X*, *A*, *N* and *R*) acting on the tibia when the knee is extended it is necessary to know their direction and the points on the tibia at which they are applied. If one of the forces is determined experimentally it is possible from these relations to calculate the magnitudes of the other 3.

The various forces acting on the tibia are shown in Figure 1. When equilibrium obtains, the clockwise and anticlockwise moments about any point will be equal, and from this relationship an equation can be derived for each of the points. If the tuberosity of the tibia is the point about which moments are taken, we have, with the notation in Figure 1, $Ra = Nb - Ac$. (The line of action of the force exerted by the ligamentum patellae passes through the point, and its moment is therefore zero). By taking moments about 2 other points, namely the insertion of the anterior cruciate ligament and the point of action of the normal force on the tibia, 3 expressions are obtained, from which the ratios between the various forces can be derived (X/R , N/R , A/R).

RESULTS

Movements in the Joint

The displacement of the patella in relation to the femur (*i.e.* the elongation of the quadriceps) during flexion for 5 subjects is represented graphically in Figure 2, and the mean curve (*I*) is given in Figure 3. The fact that this is nearly straight means that the elongation of the quadriceps is proportional to the decrease in the angle of the knee-joint.

Curves *II* and *III* in the same figure show the mean relationship between the displacement of, respectively, the points of contact on the femur and tibia and the angle of the knee-joint. Throughout flexion the femur described a movement such that new points on it constantly came into contact with the surface of the tibia (curve *II*). During the first 20° of the flexion the same type of movement occurred with the

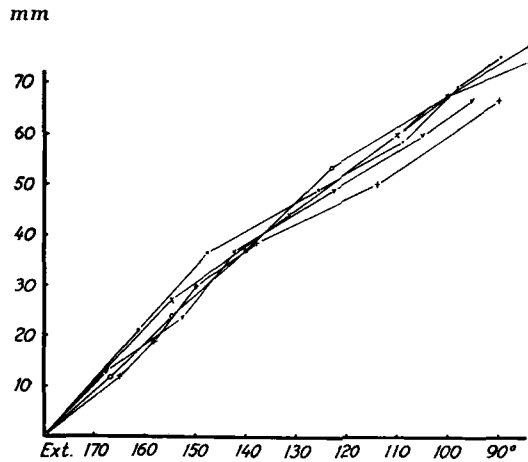


Figure 2. Relation between the displacement of the upper border of the patella (elongation of the quadriceps) and the angle of flexion of the knee for 5 subjects.

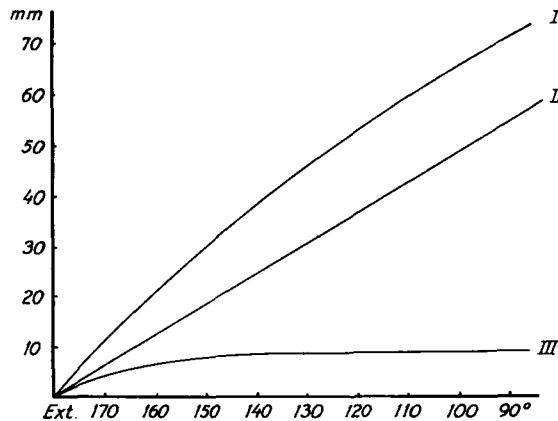


Figure 3. (I) Mean relationship between the angle of flexion and elongation of the quadriceps. (II) Displacement of the points of contact on the femur. (III) Displacement of the points of contact on the tibia.

tibial condyle in relation to the femur, new points on the tibia constantly making contact with the femur (curve III). After a flexion of 20–30 the curve turns parallel to the axis of x , which means that the same point on the tibia slipped on the femur. These findings combined show that during the first 20–30° of the flexion movement there was a combination of rocking and gliding, and not a pure rocking movement as is commonly supposed. After this position there is pure gliding of the femur against the tibia.

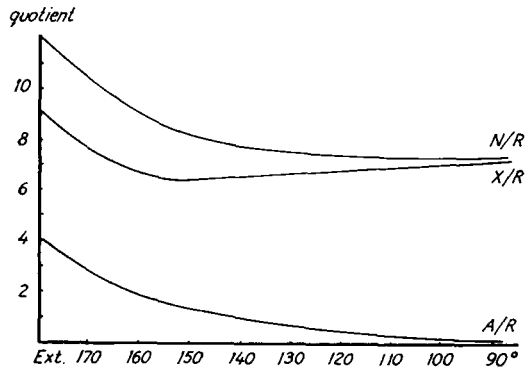


Figure 4. Mean relation between the angle of flexion and the ratio N/R , X/R and A/R (see also Figure 1).

If there were a pure rocking movement the 2 lower curves would coincide, which they do not at any phase of the flexion.

Forces Acting in the Joint

By means of the above equation the relations between the 4 forces were calculated for each position of flexion and each subject. Since the extremely large volume of data so obtained is not of general interest, only the means are reported here. The mean ratios of these forces for the various flexion positions are given in Figure 4. The curve for X/R shows the moment exerted by the quadriceps when a resistance was applied 30 cm below the joint space. It is seen that between 90° and 160° the force was largely constant, but in the last 20° of extension the ratio X/R rose from about 6 to a mean of 9. The individual values in extension ranged from 7 to 12.

The curve for the ratio A/R shows that in extension the cruciate ligament is subjected to fairly large forces but as the flexion is increased these approach zero; here the ligament is not required to prevent a forward displacement of the tibia. Thus, in this position the other 3 forces are largely in equilibrium.

It is seen from the curve for the ratio N/R that the force between the articular surfaces is fairly constant from 90° to 160° and then rises for the last 20° of the extension. Throughout the movement this pressure is greater than the pull on the tuberosity of the tibia.

DISCUSSION

Since the purpose of this study was to examine the function of the knee-joint as a mechanical system, means were used, although the individual variations were quite large. Interest was centred on the ratio X/R , which governs the action of the quadriceps. This ratio will be less favourable in the extended position chiefly because in the terminal stage the points of contact between the 2 articular surfaces move forwards. In one case in which the knee could be hyperextended by about 15° the leverage was still less favourable, and in extension the ratio X/R was 25. In the earlier literature (9) calculation of the forces in the knee was based on the moment about an imaginary axis of motion placed in the centre of the femoral condyles. This approach is mechanically unsound, as it does not take account of all the forces acting on the joint, and the rotation does not occur about an axis of small diameter, as in the hinge.

In the erect posture the knee can be extended quite easily, because the force required in extension decreases as the angle between the femur or tibia and the vertical plane diminishes; for zero angle the required force will be zero. This means that in extension the knee is for the most part stable and need only be balanced. On the other hand, in the supine position and, for instance, in exercising the quadriceps against a resistance, the unfavourable leverage in extension is apparent. The force exerted in the terminal extension will then progressively diminish.

In another study that is being conducted on the forces acting on extension of the knee at different angles, the force in the quadriceps will be calculated from the ratio X/R . A pilot study (8) has shown that the force exerted by the quadriceps falls off more rapidly than would correspond to the decrease in mechanical advantage. This is in accordance with von Schwann's law, which states that a reduction of the muscular force occurs on shortening (about 7 cm from the 90° position to extension).

In judging whether these calculations of the forces are relevant to the vital knee it is pertinent to consider whether living tissue differs from dead, and how accurately the various distances could be determined on the radiographs. So far as is known, the laws of nature, including simple mechanical principles, apply to all materials, whether vital or not. In experiments on specimens there can of course be differences in chemical composition, strength and other properties owing to, for

instance, water losses due to postmortem changes; but such alterations are not involved in the present context.

As regards the exactness with which the various points on the radiographs can be determined it is clear that small errors of estimation may have been incurred. In 5 of the subjects the points of contact between the tibia and the femur (which are the most difficult to determine accurately) were inserted; for each point the "most correct" point and 2 extreme positions, in front and behind, were marked. The quotients of the forces were then calculated for all 3 points. The range of the 3 values so obtained was not so great as to affect the conclusions materially. It was found that the "most correct" points lay very near to midway between the 2 extreme values, and were thus correctly placed.

In the anatomic literature it is stated that the medial condyle of the femur is slightly larger than the lateral one and that their curvatures are not exactly equal. This was confirmed on the radiographs. The differences in shape were small, however. In the determination of the curves and points in the sagittal plane they were taken midway between the 2 contours when the condyles were not completely congruent.

SUMMARY

On the basis of radiographic examinations of the knee-joints of 15 healthy subjects the relative movements of the articular surfaces were examined. During the first 20–30° of flexion there was combined rocking and slipping, after which there was pure slipping of the femur on the tibia. There was no pure rocking movement. From the direction and location of the various forces acting on the knee-joint in active extension the ratios between the forces were calculated. It was found that from 90 to 160° the leverage exerted by the quadriceps remained fairly constant but then decreased, so that a greater effort was required to extend the joint through the last 20°.

RESUME

Sur la base d'examen radiographiques de l'articulation du genou chez 15 sujets sains, il a été étudié les mouvements relatifs des surfaces articulaires. Durant les degrés 20 à 30 de flexion, il y avait une combinaison de tremblement et de glissement, après quoi, il y avait un pur glissement du fémur sur le tibia. On n'a pas observé de pur tremblement. En partant de la direction et de la localisation des différentes

forces opérant sur l'articulation du genou en extension active, il a été calculé le rapport entre les forces. On a constaté que de 90 à 160°, le moment du quadriceps reste à peu près constant pour décroître ensuite, de sorte qu'un plus gros effort est nécessaire pour étendre l'articulation à travers les derniers 20 degrés.

ZUSAMMENFASSUNG

Auf der Grundlage von röntgenologischen Untersuchungen der Kniegelenke von 15 gesunden Personen wurden die relativen Bewegungen der Gelenksflächen untersucht. Während der ersten 20–30° der Beugung war eine kombinierte Wiege- und Gleitbewegung, hernach reines Gleiten des Femur auf der Tibia zu beobachten. Alleinige Wiegebewegung wurde nicht gesehen. Aus der Richtung und Lage der verschiedenen Kräfte, die auf das Kniegelenk während aktiver Streckung wirken, wurde das Verhältnis zwischen den Kräften berechnet. Es wurde gefunden, dass von 90 bis 190° die vom Quadriceps ausgeübte Hebelkraft ziemlich konstant war, jedoch dann abnahm, so dass eine grössere Anstrengung notwendig war um das Gelenk während der letzten 20° zu strecken.

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