ADVANCEMENT OF THE TIBIAL TUBEROSITY

A BIOMECHANICAL STUDY

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The effects of advancement of the tibial tuberosity by inserting bony wedges was studied on cadaveric specimens of the knee. The geometry, the contact areas and the forces acting on the patellofemoral joint were investigated, and the forces acting on the tibiofemoral compartment were calculated.

A 1 cm advancement was found to be optimal in reducing the high patellofemoral joint forces occurring at 90° and 110° of flexion, whilst causing least reduction of the contact areas; the stresses on the joint were reduced significantly. Advancement by 2 cm and by 3 cm drastically reduced the congruity and the size of the contact area. It was also shown that 2 cm and 3 cm advancement caused an increase in forces at the patellofemoral joint and also in the tibiofemoral joint in a direction tangential to the articular surfaces.

Anterior advancement of the tibial tuberosity, by the introduction of a bony wedge, has been advocated for the relief of pain in the patellofemoral compartment. The operation is commonly known as Bandi's or Maquet's operation, having been described by both authors (Bandi and Brennwald 1974; Maquet 1976). The biomechanical basis for this operation has been that advancement of the tibial tuberosity increases the moment arm and thus the mechanical advantage of the patellar ligament; this reduces the forces acting along it and thus the resultant force across the patellofemoral joint. It is claimed that the stresses in the patellofemoral compartment would thereby be reduced. But anterior advancement of the tibial tuberosity must alter the contact between the femur and the patella, and hitherto this has not been investigated. Reduction of the forces acting across the patellofemoral joint does not necessarily reduce the stresses, since these are dependent not only on the forces but also on the contact area between the articular surfaces.

The present study investigates the effect of tuberosity advancement on the geometry, the patterns of contact, and the forces acting on the patellofemoral compartment. It further investigates the changes produced in the forces acting on the tibiofemoral compartment; operations are often carried out on one compartment of the knee without regard for consequences on the

other. Experiments were carried out through a range of flexion from 0° to 110°, and with the tibial tuberosity in the normal position and advanced by 1, 2 and 3 cm. The results obtained through these varied conditions enabled us to determine the optimal thickness of the wedge to be used.

METHODS AND MATERIAL

Geometry of the patellofemoral joint. The geometry of the joint was studied by taking lateral radiographs of an intact cadaveric knee joint at a number of angles of flexion and then repeating the films after introducing metal wedges of 1, 2 and 3 cm thickness behind a split tibial tubercle. The length of the split down the anterior crest of the tibia for the introduction of the wedge was also studied; the effect of splits of 5, 10 and 15 cm length were examined.

Contact in the patellofemoral compartment. Nine human knee joints obtained at autopsy were used for this study. Those which had been stored below -20°C were thawed just before use. The ligaments, menisci and most of the connective tissue were kept intact but the muscles were removed. A 7 cm coronal split was made behind the tibial tuberosity. The contact area at the patellofemoral joint was determined to show its shape and location at various angles of flexion. Contact maps were constructed using the technique and the apparatus (Fig. 1) which we have described elsewhere in detail (Seedhom and Tsubuku 1977; Seedhom *et al.* 1979).

The contact area at any angle of flexion was determined by introducing a small amount of silicone rubber casting material between the femur and the patella at the region of contact. The patella was then replaced and a small amount of tension (20–30 N) was applied along the quadriceps tendon to ensure contact between the patella and the femur. Such small loads were

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Fig. 1

Fig. 2

Figure 1—The experimental apparatus. Figure 2—Typical contact areas marked on replicas of the femur and the patella.

sufficient for our purpose since the location of contact is independent of the amount of tension applied. We were able to note the changes in congruence with each position and wedge thickness, and to observe the relative changes in size of the contact area.

When the casting material had set, the patella was lifted and the cast removed. The whole casting procedure was repeated at the same angle of flexion but with the tibial tuberosity advanced by 1, 2 and 3 cm. This whole sequence was then repeated at other angles of flexion. At the areas of contact between femur and patella the silicone rubber was squeezed out, leaving holes in the casts. When the castings were completed, replicas were made of both the femur and the patella using the method described by Dransfield (1965). The silicone rubber castings were then placed, in turn, on the replica femur and patella, and the areas of contact marked on their surfaces (Fig. 2). In this manner a series of contact maps were obtained for both femur and patella for each joint.

Forces on the joint. For the purposes of this study the activity of rising from a chair without the aid of the arms was used to investigate the effect of advancement on forces in the knee. This particular activity was chosen because it is one where the angle of knee flexion is large, as are the forces in both the tibiofemoral and the patellofemoral compartments. It is also an activity which is essential for the mobility and independence of patients. The forces at the knee were calculated by kinesiological techniques, external forces being deduced by using force platforms, high-speed ciné cameras and electromyographic recorders. This data was applied to a mathematical model, which allowed the forces about the joint to be calculated (Ellis, Seedhom and Wright 1984).

In this earlier study, a number of subjects were tested, and the forces acting on the knee were calculated

during the activity of rising from a chair with and without the aid of the arms. Radiographs of each of these subjects' knees were available, so comparison with the radiographs of the cadaveric knees used in the present study made it possible to select a subject who had a "matching" knee. This cadaveric knee was then used to study the effect of advancing the tibial tuberosity on the geometry of the joint. The geometrical changes occurring in the cadaveric knee after advancing the tuberosity different distances could then be incorporated in the mathematical model of this subject; from this the forces acting on the subject's "operated" knee while rising from a chair could be analysed.

RESULTS

Effect of operation on the geometry of the joint. Figure 3 is a tracing of a typical radiograph taken at 90° of flexion with a 2 cm wedge, whilst Figure 4 is a similar tracing also at 90° but with a 3 cm wedge. It can be seen that, with the knee at 90°, the moment arm D , the distance between the point of contact of femur and tibia and the line of action of the patellar ligament, is hardly altered between the 2 cm and the 3 cm wedges. The effect of a

Table 1. The moment arm of the patellar ligament related to the angle of knee flexion and advancement of the tibial tubercle

Advancement of tibial tubercle (cm)	Moment arm (mm) at various angles of knee flexion				
	0	30	60	90	110
0	41	45	42	38	38
1	46	52	48	41	39
2	52	57	50	43	40
3	60	60	55	45	44

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Tracings of radiographs of specimens to show the effect of wedge insertion. Figures 3 and 4—To show the small change in the moment arm (D) of the patellar ligament caused by changing a 2 cm for a 3 cm wedge at 90° flexion. Figures 5 and 6—To show the effect of advancement on the angle (β) between the quadriceps tendon and the patellar ligament.

wedge is, however, greater at smaller angles of flexion. Measurements of the moment arm for the force in the patellar ligament are given in Table I; these include the different thicknesses of bony wedge and the ranges of knee flexion from 0° to 110°.

The lack of dramatic alterations does not mean that the thickness of the wedge is of no consequence. As can be seen from Figures 5 and 6, the angle between the patellar ligament and the quadriceps tendon (angle β) is increased by the insertion of a wedge. The larger this angle, the smaller will be the resultant of the forces in tendon and ligament tending to compress the patellofemoral joint, assuming these forces themselves are unchanged.

Table II. Distal shift of the patella related to length of tibial split and to tubercle advancement

Advancement of tibial tubercle (cm)	Distal shift (mm) at various lengths of tibial split		
	5 cm split	10 cm split	15 cm split
1	6	5	4
2	13	10	9
3	24	18	16

The tracings and maps also show that the position of the patella in respect to the femur alters greatly in response to the wedges, as does the congruence of the joint and the contact area. The patella not only rotates about its horizontal axis and is in contact with a different region of the femur for each angle of flexion, but it also moves inferiorly towards the tibial plateau as the tuberosity is advanced anteriorly. This downward movement of the patella is a function not only of the thickness

of the wedge but also of the length of the split that has been made in the bone. This can be seen in Figure 7, and Table II shows that the longer the split, the smaller will be the consequent downward movement of the patella.

Fig. 7

Diagram to show the influence of the length of the split in the tibia on the distal shift of the patella (d) and the rotation of the patella (β).

Fig. 8

Diagrams of typical contact areas on the femur at various degrees of flexion with different wedges. The proximal part of the joint surface is at the top of the diagram.

Contact areas. Figures 8 and 9 show the position of the areas of contact on the femur and patella respectively. The positions of these areas on the femur have not altered greatly with wedge insertion, but the size of the areas has in general decreased progressively as the thickness of the wedge has increased. On the other hand, the pattern of contact on the patella shows that the positions of contact have changed greatly. Changes are minimal with a wedge thickness of 1 cm but with a 2 cm wedge there is a marked change—the contact areas become concentrated on the proximal part of the patellar surface. At over 90° of flexion with a 3 cm wedge there is no contact between the femur and the patella. Figure 10 shows the areas of contact as traced from the replica casts. It corroborates the appearances seen in Figures 8 and 9, and summarises the changes in contact area under the small load applied for the three wedge thicknesses and the five positions of flexion used in the study.

Forces at tibiofemoral and patellofemoral joints. Figure 11 shows the calculated force normal to the surface of the tibiofemoral joint. It is seen that, in general, forces have been reduced by tubercle advancement, with the exception of a wedge thickness of 3 cm at 110° flexion when the force becomes four times greater than in the intact knee. Figure 12 shows tibiofemoral forces in a direction tangential to the joint surfaces. This force is normally

Fig. 9

Diagrams of contact areas on the patella at various degrees of flexion with different wedges. The proximal part of the joint surface is at the top, and the lateral edge is to the right.

Fig. 10

The relationship between patellofemoral contact areas, the angle of flexion of the knee and advancement of the tibial tubercle.

Fig. 11

The relationship between the force normal to the tibiofemoral joint, the angle of flexion of the knee and advancement of the tibial tubercle.

resisted by the soft tissues and the cruciate ligaments; it has decreased with larger displacement at 0° and 30° flexion. The changes at 60° flexion are not significant but in greater flexion at 90° and 110°, the tangential forces are increased by more than 25% as the wedge thickness rises to 3 cm.

Forces at the patellofemoral joint are shown in Figure 13. These decrease dramatically with increased wedges at 0°, 30° and 60°, at which angles the joint forces are in any case small. The forces at 90° and 110° fall with a wedge thickness of 1 cm but at greater thicknesses they tend to increase. At 110°, with a 3 cm wedge, there was no contact between femur and patella, but only between the quadriceps tendon and the trochlea of the femur.

CONCLUSIONS

Several conclusions can be drawn from these results. The moment arm of the patellar ligament is not greatly influenced (especially at high angles of flexion of the knee) when the tibial tubercle is elevated by bony wedges of increasing thickness. The influence of the wedge was mainly to change the angle subtended by the patellar ligament and the quadriceps tendon, thus affecting the resultant force acting on the patellofemoral surface.

The pattern of contact in the patellofemoral joint is altered minimally by a 1 cm wedge, but greatly changed by displacement of 2 to 3 cm. The position of the areas of contact on the femur remain virtually unaltered, but on the patella the contact areas become gradually concentrated on the proximal portion as tibial tuberosity advancement is increased. The contact areas, although obtained with only small loads on the patellofemoral joint, tended to be greatly reduced with larger wedges.

As the thickness of the wedge increases, the value of the forces acting on the tibiofemoral joint along the axis of the tibia is reduced. However, a very large and undesirable change occurs in this force at 110° with a wedge thickness of 3 cm. A general increase occurs in the tangential forces at the tibiofemoral joint.

Fig. 12

The relationship between the force tangential to the articular surfaces of the tibiofemoral joint, the angle of flexion of the knee and advancement of the tibial tubercle.

Fig. 13

The relationship between the force at the patellofemoral joint, the angle of flexion of the knee and advancement of the tibial tubercle.

Force at the patellofemoral joint is reduced throughout the tested range of flexion by a wedge thickness of 1 cm. With larger wedge thicknesses, at 90° and 110°, the force increases beyond an already high level, but there is some reduction in force at the lower angles, at which angles the forces are already small and less important.

It therefore seems that an advancement of 1 cm achieves the optimal reduction of forces in the knee joint, with minimal disturbance of the pattern of contact, and minimal reduction in the size of the area of contact; this is therefore the recommended thickness for a wedge. The small amount of displacement also gives a much more desirable cosmetic result with less change in the appearance of the knee, and less trouble with necrosis of the skin over the tibial tuberosity. To minimise the distal

shift of the patella caused by 1 cm advancement of the tibial tuberosity, the split in the tibia should be at least 10 cm long.

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