ORIENTATION OF THE CRUCIATE LIGAMENT IN THE SAGITTAL PLANE

A METHOD OF PREDICTING ITS LENGTH-CHANGE WITH FLEXION

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We have studied the kinematics of the knee in the sagittal plane, using a four-bar linkage as model, and assuming that a "neutral fibre" in each ligament remains isometric throughout flexion. We devised a computer program to calculate the distance separating any pair of points, one on each bone, for various cruciate attachments at various angles of flexion.

The parameters for the linkage in four cadaveric knees were obtained by marking the centre of attachment of the cruciate ligaments with tacks and taking lateral radiographs. The movements of the bones were then calculated, in the computer model, for various attachments of "replacement" ligament fibres, the distance between the attachment sites being plotted against the angle of flexion.

It was then possible to define zones around the isometric attachment points within which changes in length would be *predictable*. Our results show that the position of the femoral sites of attachment of both anterior and posterior cruciate replacement was more critical than that of the tibial attachments.

Cruciate ligament injury is a significant cause of instability and long-term morbidity of the knee, and intra-articular reconstruction has become more commonplace. In a computer model of the sagittal plane of the knee, we have calculated the change in distance between various possible attachments for ligament replacements during the range of flexion, and have identified zones around the normal insertion on the femur for which the length-change of a replacement can be predicted. When at operation a change in length with flexion is observed, then a knowledge of these zones can help the surgeon to reposition the attachment to achieve a more isometric configuration.

THEORY

A number of authors have discussed the design of the knee as a four-bar linkage consisting of the two cruciate ligaments with the femoral and tibial bone between their attachments (Strasser 1917, cited in Steindler 1955;

Kapandji 1970; Menschik 1974; Goodfellow and O'Connor 1978; Müller 1983). For analysis, it is assumed that a neutral fibre within each ligament remains at a constant length (isometric) throughout the arc of flexion. The fixed measurements of the linkage are the lengths of these two neutral fibres and the distances on each bone between their attachments *as viewed in the sagittal plane*. The instant centre of the joint, the axis of flexion at any stage, is the point of intersection of the neutral fibres (Fig. 1). A hypothetical fibre which lies in front of this axis will lengthen as the knee is flexed, while fibres lying behind the axis will shorten. This can be deduced by examining the direction of the velocity components of such fibres during flexion of the femur on a fixed tibia (Fig. 2).

This conclusion is consistent with the observation reported by various authors that the anterior fibres of the anterior cruciate, the posterior cruciate, and the medial collateral ligaments all stretch during flexion while their posterior fibres slacken (Wang and Walker 1973, 1974; Crowninshield, Pope and Johnson 1976; Arms et al. 1983, 1984). All the fibres of the lateral collateral ligament slacken during flexion (Edwards, Lafferty and Lange 1970). From these observations we may deduce that the flexion axis penetrates the medial collateral and the two cruciate ligaments, but lies in front of the lateral collateral ligament. The evidence justifies our assumption that "neutral fibres" pass through the flexion axis and stay isometric throughout the arc of flexion. The points of attachment of these neutral fibres are referred to below as the isometric site.

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Fig. 1

The orientation of the four-bar linkage in three positions of flexion. *AB*, the anterior cruciate neutral fibre; *CD*, the posterior cruciate neutral fibre; *AC*, tibial link and *DB*, femoral link. The instant centre of flexion is at the intersection of the two cruciate ligament links. Line *E* is the course of the instant centre with the femur moving on a fixed tibia.

Fig. 2

Velocity diagram for fibres in front of, through, and behind the flexion axis at *O*. Fibre *AB* is in front of the flexion axis, and the direction of the velocity of *B* is perpendicular to a line drawn from *O* to *B*. This velocity may then be resolved into components parallel to the line of the fibre *AB* and perpendicular to it. The component parallel to *AB* indicates that *B* is moving away from *A* and the fibre *AB* is lengthening. Fibre *AC* passes through the flexion axis and there is no component tending to lengthen or shorten the fibre. Fibre *AD* lies behind the flexion axis, the point *D* approaches *A* and the fibre *AD* is shortening.

The object of ligament reconstruction is to re-establish normal joint kinematics by restoring the relationship between the joint surfaces and the ligament system. The effects of a ligament on the joint kinematics and mechanics depend on its physical dimensions, attachment sites and mechanical properties. The surgeon attempts to replace a ligament with a structure of comparable mechanical properties which he places along the line of the neutral fibre of the original ligament so that the substitute is in an approximately isometric state throughout the range of flexion.

There are five possible outcomes for a single ligament position in terms of change of length as the knee is passively moved from full extension to full flexion:

1. No length change: the ideal isometric position.
2. Increase in length: the neutral fibre is in front of the flexion axis throughout the flexion range.
3. Decrease in length: the fibre is behind the flexion axis throughout the flexion range.
4. Initial shortening followed by lengthening: at full extension the fibre lies behind the flexion axis, but with flexion moves to lie in front. The overall change in length will depend on the relative sizes of the arcs of flexion which take place behind or in front of the flexion axis.
5. Initial lengthening followed by shortening: the converse of the above (No. 4).

A ligament, a replacement, or a graft may contain some fibres which show each of these five patterns of behaviour. We have examined and defined the zones around the isometric attachment sites where outcomes 2 to 5 will pertain.

MATERIALS AND METHODS

Specimens. Four fresh cadaveric specimens from adult male knees were stored frozen until dissected. Skin and soft tissues were removed to expose the joint capsule and the ligamentous structures, but retaining the quadriceps tendon. Except for minor degenerative changes in the patellofemoral joint of two specimens, there was no evidence of joint pathology.

Anterior and posterior arthrotomies were performed to identify the cruciate ligaments; these were stripped of their synovial covering. The femur was then sectioned sagittally through the intercondylar notch with a fine-bladed saw, avoiding injury to the cruciate attachments. The centres of the origins and insertions of the cruciate ligaments were each marked by a metal tack with a 2 mm head. The femoral sections were anatomically reduced and held with cross-bolts.

A five- to six-newton load was applied to the quadriceps tendon to hold the knee in full extension.

Radiographs of the specimens were then taken, one view including a radiopaque metal rule in the plane of the intercondylar notch to assess magnification of the image. After radiography the specimens were dissected to check the positions of the markers relative to the centres of the attachment sites of the cruciate ligaments. Measurements from the lateral radiographs enabled us to reconstruct the four-bar linkage, making appropriate adjustments if a tack had not been located centrally within the site of bony attachment.

Each of the four specimens was studied independently. The parameters for the cruciate linkage appropriate to each specimen were used in a previously developed computer program.

Computer simulation. The movement of any defined four-bar linkage may be described mathematically and therefore lends itself to computational analysis. Given the parameters of the linkage, the relative movement of the bones can be calculated; this then defines the relative positions of any two points (one on each bone) during flexion. We performed calculations for the range from

full extension to 140° of flexion. The coordinates of possible attachment points for a "replacement" ligament fibre were then fed into the program and the change in distance between them plotted against the flexion angle.

Fig. 3

Adapted from Odensten and Gillquist (1985) to show the dimension γ . The diagrams of the lower right femur show the medial surface of the right lateral condyle after removal of the medial condyle. The outline of the femoral attachment of the anterior cruciate ligament is shown at distance γ from the "over-the-top" site.

Fig. 4a

Figure 4a – Femoral attachment of an anterior cruciate fibre moved anteriorly by 5 mm, posteriorly by γ mm, and inferiorly by 5 mm. The tibial attachment remained in its normal isometric site.

Fig. 4b

Figure 4b – Femoral attachment of a posterior cruciate fibre moved anteriorly, posteriorly, and inferiorly by 5 mm respectively. The tibial attachment remained at its isometric site.

Fig. 4c

Figure 4c – Tibial attachment of an anterior cruciate fibre moved 10 mm anteriorly and posteriorly along the tibial eminence. The femoral attachment remained at its isometric site.

Changes in length with varying angles of flexion. The length L at any angle is expressed as a ratio of the length L_0 at full extension.

RESULTS

Table I gives the parameters of the four-bar linkage in the four specimens and the angle between the femoral link and the roof of the femoral notch. These were measured from lateral radiographs taken in full extension. On the bottom line, values are given for the distance γ , described by Odensten and Gillquist (1985). This is the distance from the centre of the femoral insertion of the anterior cruciate ligament in a posterior and superior direction to the point where the femoral shaft meets the lateral femoral condyle (Fig. 3). This point is of interest in the "over-the-top" method of replacing an anterior cruciate ligament.

We give examples of the length-change outcomes which result from moving the attachments of the anterior cruciate ligament in Figure 4. This shows the results of movement of the femoral attachment of both cruciate ligaments and of the tibial attachment of the anterior cruciate ligament. Figure 5 plots the difference in change in length between the most anterior and the most posterior fibres of a graft 6 mm in diameter when its neutral fibre is at the isometric point on both tibia and femur.

Fig. 5

Change in relative fibre length with change in angle of flexion for the anterior and posterior fibres of an anterior cruciate graft 6 mm in diameter.

Using multiple coordinates, we were able to define zones around the isometric point of attachment where the length-change of any replacement could be predicted. Figure 6 shows zones radiating from the femoral attachment of the anterior cruciate, assuming the tibial attachment to be at the normal isometric position. Figure 7 shows similar zones radiating from the femoral attachment of the posterior cruciate.

In Figure 8 we show graphs which plot the percentage change in length at 90° and 140° of flexion against the position of attachment of the neutral fibre for the mean dimensions of the four-bar linkage of the four specimens. For an anterior cruciate fibre, they show the result of moving the femoral attachment anteriorly and

posteriorly along the line of the femoral link, moving the same attachment perpendicular to the femoral link, and moving the tibial attachment anteriorly and posteriorly along the line of the tibial plateau. Figure 9 shows the effect of moving the femoral attachment of a posterior cruciate fibre.

MEDIAL ASPECT OF LATERAL FEMORAL CONDYLE

Fig. 6

The femoral attachment of the isometric fibre of the anterior cruciate with zones of attachment which would cause length-change during flexion. L, lengthening; S, shortening. Capital letter indicates the overall effect for full flexion. The first letter indicates the initial effect as the knee is flexed from full extension. Thus, sL indicates initial shortening followed by lengthening, the overall effect being lengthening.

LATERAL ASPECT OF MEDIAL FEMORAL CONDYLE

Fig. 7

The femoral attachment of the isometric fibre of the posterior cruciate with zones of attachment which would cause length-change during flexion. L, lengthening; S, shortening - as in Figure 6. The first letter indicates the initial effect as the knee is flexed from full extension.

Fig. 8a

Fig. 8b

Fig. 8c

The percentage change in length related to the displacement of the attachment of an anterior cruciate fibre relative to the isometric site. Figure 8a – Femoral attachment moved along the line of the femoral link, tibial attachment being in the isometric position. Figure 8b – Femoral attachment moved perpendicular to the femoral link, tibial attachment being in the isometric site. Figure 8c – Tibial attachment moved anteriorly and posteriorly along the tibial eminence, femoral attachment at the isometric site.

Fig. 9a

Fig. 9b

The percentage change in length related to the displacement of the attachment of a posterior cruciate fibre relative to the isometric site. Figure 9a – Femoral attachment moved along the line of the femoral link, tibial attachment at the isometric site. Figure 9b – Femoral attachment moved perpendicular to the femoral link, tibial attachment at the isometric site.

DISCUSSION

Isometric positioning of a cruciate replacement will allow the knee to move through its full range of flexion without placing excessive tension on the graft and will therefore reduce the risk of graft disruption. A non-isometric position will give problems. If its position causes it to lengthen as the knee is extended and it has been fixed with the knee in flexion, then either there will be a flexion contracture or the graft will be overstretched and may rupture. If the same graft is fixed in a position of full extension, it will be lax during the whole range of flexion and will not contribute to normal guidance of movement.

At operation, the correct positioning of the *tibial* attachment for both anterior and posterior cruciate ligaments is relatively straightforward. Finding the

correct isometric points for the femoral insertions is more difficult. It is unfortunate that, for a given error, the relative change in length is proportionately greater in malposition of the femoral than of the tibial site (Fig. 8). Thus the more difficult site is also the more critical. Our results narrow this variation even more, showing that anterior and posterior malposition along the line of the femoral link is a more important change than that in the superior and inferior line. This observation is more marked for the anterior than for the posterior cruciate ligament (Figs 8 and 9). For practical purposes the line of the femoral link may be taken as the line of the notch roof as is shown by the small angles in the penultimate line of Table I.

The neutral fibres of the *normal* anterior cruciate ligament are believed to remain at a constant length as

Table I. Results of radiographic measurement of the parameters for the sagittal view of the four-bar linkage in four cadaveric knees

	Specimens			
	1	2	3	4
Length of anterior cruciate (mm)	30	33	32	33
Length of posterior cruciate (mm)	28	29	24	33
Length of tibial link (mm)	28	31	29	34
Length of femoral link (mm)	12	16	15	15
Angle between femoral link and the roof of the notch (degrees)	10	5	6	7
γ displacement of "over-the-top" femoral attachment (see text and Fig. 3) (mm)	11	12	14	10

the knee is passively moved through a full flexion range. The fibres attached anterior to the neutral fibre on the tibia are inserted posterior to the neutral fibre on the femur, the posterior fibres on the tibia insert anteriorly on the femur (Norwood and Cross 1979). This orientation minimises the length-change during flexion for the non-isometric fibres.

When a cruciate ligament is reconstructed, length changes can be minimised by placing the centre of the graft at the isometric point. Daniel, Penner and Burks (1987) recommend that at the time of operation for cruciate reconstruction the distance between the central points of the graft attachment sites on the femur and the tibia should not vary by more than 2 mm during flexion from 0° to 90°. This arc of movement was given because full flexion at that stage is blocked by the requirements of sterility, surgical position and drapes. The surgeon should, however, be aware that the additional change in length between 90° and 140° of flexion may be greater than that between 0° and 90°. This is especially important when anterior position of the graft on the femur produces lengthening with knee flexion (Fig. 8a).

One popular mode of aligning an anterior cruciate graft is the "over-the-top" method of MacIntosh and Tregonning (1977). This orientation is non-isometric; there is a decrease in the distance between attachments as the knee is flexed (Fig. 4a). However, this change in length can be reduced, either by moving the tibial attachment site anteriorly or by reducing the value of γ by making a trough in the bone at the back of the lateral femoral condyle, or by both changes. This confirms the findings of Daniel et al. (1987) of graft length-changes in these configurations in cadavers.

Conclusions. In the sagittal plane the knee can be considered as a four-bar linkage. A computer program demonstrated the changes in length of "replacement" ligament fibres at different sites of attachment, and confirmed cadaver measurements by other authors.

Zones around the isometric sites for femoral attachment of the cruciate ligaments allow this length-change to be predicted.

Correct positioning of the attachment sites is more critical at the femoral than the tibial sites, and variation in the line of the femoral link or notch roof is more important than variation perpendicular to this line.

The change in length of a non-isometric graft may be proportionally greater from 90° to 140° than from 0° to 90°.

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