

# CAN MUSCLE CO-CONTRACTION PROTECT KNEE LIGAMENTS AFTER INJURY OR REPAIR?

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**A computer-based model of the knee was used to study forces in the cruciate ligaments induced by co-contraction of the extensor and flexor muscles, in the absence of external loads. Ligament forces are required whenever the components of the muscle forces parallel to the tibial plateau do not balance.**

**When the extending effect of quadriceps exactly balances the flexing effect of hamstrings, the horizontal components of the two muscle forces also balance only at the *critical flexion angle* of 22°. The calculations show that co-contraction of the quadriceps and hamstring muscles loads the anterior cruciate ligament from full extension to 22° of flexion and loads the posterior cruciate at higher flexion angles. In these two regions of flexion, the forward pull of the patellar tendon on the tibia is, respectively, greater than or less than the backward pull of hamstrings. Simultaneous quadriceps and gastrocnemius contraction loads the anterior cruciate over the entire flexion range. Simultaneous contraction of all three muscle groups can unload the cruciate ligaments entirely at flexion angles above 22°. These results may help the design of rational regimes of rehabilitation after ligament injury or repair.**

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Increasing participation in athletic activity has led to a corresponding increase in soft-tissue injury among the general population. Hirshman, Daniel and Miyasaka (1990), reporting from the accident service of one hospital in the USA, gave the incidence of knee ligament injuries as about one per 1000 of the population per year, with 61% of these injuries incurred during sport and a further 10% in traffic accidents. More than 50% of ligament injuries were in the 15- to 30-year age range.

Ligament injuries may lead to excessive joint laxity and instability, which in turn allow repeated injuries and progressive damage to the menisci and the articular surfaces (Sachs et al 1990). There is therefore a case for treatment, but appropriate forms of treatment are still controversial. Conservative treatment may be by a short period of immobilisation followed by a period of protected weight-bearing before attempts are made to recover full function through various exercises. In the event of a partial injury to a ligament, early exercises may be designed to avoid loading the injured ligament.

After early diagnosis, operation is increasingly preferred (Andersson, Odensten and Gillquist 1991). Tendon grafts are used to repair or replace ligaments, but because of their limited availability and complications at the donor site, prosthetic ligaments have been developed and used for augmentation or replacement (Kennedy et al 1980; Macnicol, Penny and Sheppard 1991). After surgery of any type, rehabilitation has to be carefully supervised to protect the graft or prosthesis from excessive force. Clearly defined stages over a period of up to one year are advised to control return to full activity (Daniel and Stone 1990; Noyes, Barber and Mangine 1990). Long periods of limited movement and muscle activity, however, can lead to joint fibrosis and muscle atrophy (Shelbourne et al 1991). Isolated quadriceps exercises are usually recommended for anterior cruciate rehabilitation, but hamstring exercises may be more beneficial (Solomonow et al 1987; Hirokawa et al 1991).

In order to devise exercises which will either load or protect individual ligaments, and to determine the corresponding ranges of flexion at the knee, a general understanding of the mechanical interactions between

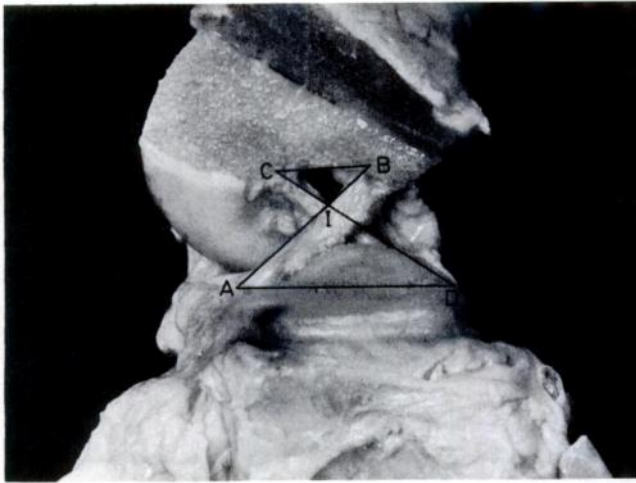


Fig. 1

A human knee with the lateral femoral condyle removed, to expose the cruciate ligaments. A diagram of the cruciate linkage ABCD is superposed. The instantaneous centre of the linkage lies at I. The flexion axis of the joint passes through I.

muscles and ligaments is necessary. The aim of this paper is to analyse the mechanics of the knee when the flexor and extensor muscles apply force simultaneously without moving it, and to determine how various combinations of muscle action load the cruciate ligaments.

To calculate the joint forces at different flexion angles, it is necessary first to develop a geometrical model to study the movement, during flexion and extension, of the lines of action of the forces transmitted by the muscles, the ligaments and the articular surfaces. A two-dimensional model in the sagittal plane is used to keep the analysis as simple as possible, and only the cruciate ligaments are considered. The development of the model has previously been described (O'Connor, Shercliff and Goodfellow 1988, 1989; O'Connor et al 1990a) as has its experimental verification (O'Connor et al 1990b), but a brief summary is given here.

## KNEE MODEL

**The cruciate linkage.** The model of the knee is based on the four-bar linkage ABCD (Fig. 1). Two links represent the anterior cruciate ligament, AB, and the posterior cruciate ligament, CD, and two links, BC and AD, join their points of attachment on the femur and on the tibia. Changes in the angle of flexion of the joint result in equal changes in the angle between the femoral link BC and the tibial link AD. Simultaneously, the ligament links rotate about their attachment sites on the two bones. From the geometry of Figure 1, the directions of the ligament links can be calculated for any angle of flexion and coincide with those of the forces transmitted by the model cruciate ligaments.

**The instantaneous centre of the linkage.** The instantaneous centre of the linkage lies at the point I at which the

ligament links cross (Fig. 1). The flexion axis of the joint, about which the bones flex and extend, also passes through I. Because the geometry of the linkage changes during flexion and extension, the instantaneous centre moves backwards and forwards relative to the two bones and, as a result, the femur rolls as well as slides on the tibial plateau. These rolling movements were described by Weber and Weber in 1836.

**Models of the bones.** An elaboration of the model of the cruciate linkage is shown in Figure 2, which includes representations of the femur and the tibia. The tibial plateau of the model is flat. The shape of the corresponding femoral condyle is nearly circular and is calculated from the theorem that the common normal to the articular surfaces at their point of contact must pass through the flexion axis of the joint. This is necessary to avoid separation or interpenetration of the bones or stretching or slackening of the ligaments during passive movements of the joint. The contact point between the bones follows the instantaneous centre, moving backwards during flexion and forwards during extension, from  $X_1$  in Figure 2a to  $X_3$  in Figure 2c.

**Lines of action of ligament and contact forces.** The line of action of the contact force between the articular surfaces must pass through their point of contact, and, if the articular surfaces are frictionless, it must also lie along the common normal IX (Fig. 2). The lines of action of the ligament and contact forces therefore intersect at the flexion axis. These forces can have no moment about the flexion axis and they cannot, by themselves, induce or resist extension or flexion. Movements can be induced or resisted only by a force which does not pass through the flexion axis. The lever-arm of such a force is the perpendicular distance from the flexion axis to its line of action.

**Muscle tendons.** Lines representing the tendons of the quadriceps, hamstring and gastrocnemius are included in the model shown in Figure 3. P, the centre of force of the patella, moves on a circular path centred at T (Fig. 2), the centre of the trochlear facet of the femur. At flexion angles greater than  $70^\circ$  the quadriceps tendon wraps around the front of the femur, forming the 'tendo-femoral' joint (Goodfellow, Hungerford and Zindell 1976).

As shown in Figure 3, the lines of action of the muscle, ligament and contact forces all vary systematically during flexion and extension as the tendons and ligaments rotate about their points of insertion and as the femur rolls backwards and forwards. From the point of view of ligament loading, it is important to note that the patellar tendon exerts a forward as well as an upward pull on the tibia, except in the highly flexed knee; that the hamstrings exert a corresponding backward pull except near extension; and that the gastrocnemius exerts a forward pull on the tibia over the entire flexion range.

**Lever-arms of the muscles.** The lengths of the lever-arms of the three main muscle groups have been calculated

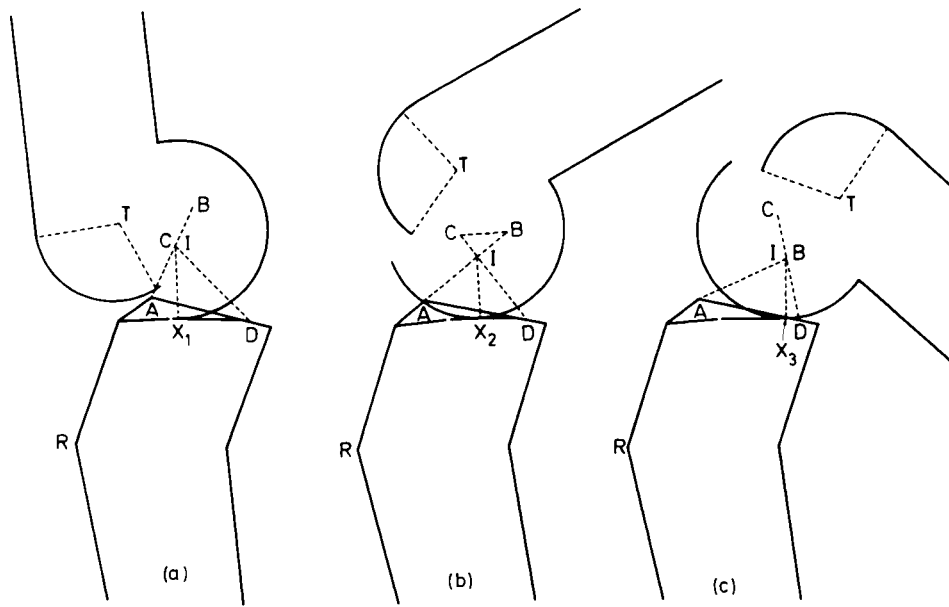


Fig. 2

Models of the femur and the tibia connected by the cruciate linkage ABCD of Figure 1; (a) in full extension, (b) at 70° and (c) at 140° of flexion, as drawn by computer. The tibial plateau is flat and is shown horizontal. In extension (a) the straight leg is shown inclined at 13° to the vertical. The shape of the contacting femoral condyle is such that separation or interpenetration of the articular surfaces and stretching or slackening of the cruciate links AB or CD do not occur. The trochlear facet of the femur is a circular arc centred at T.

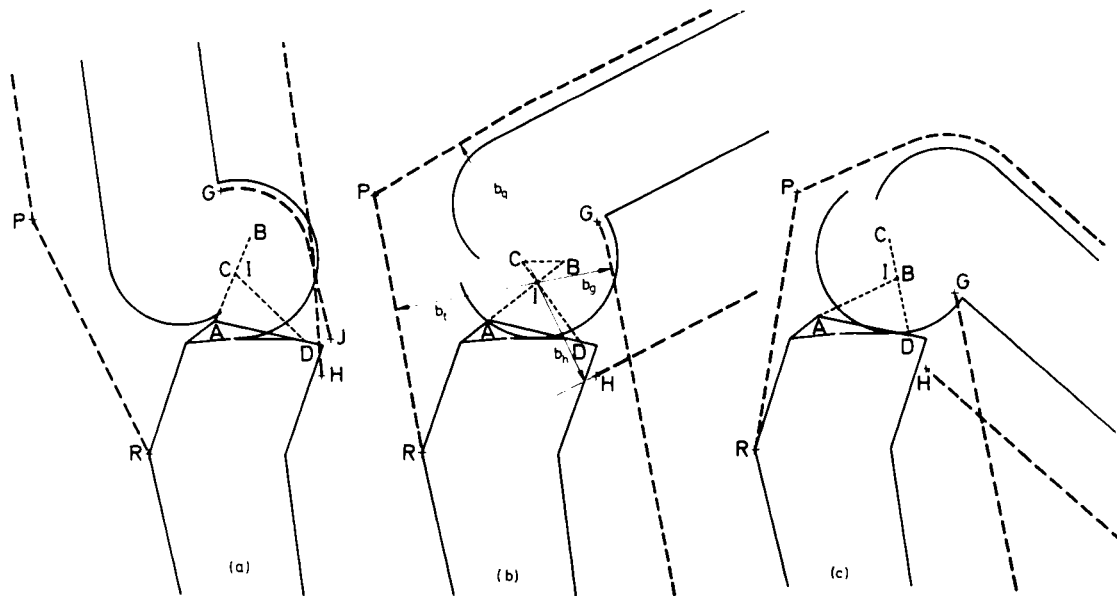


Fig. 3

The model used in Figure 2 with lines added to represent the tendons of the quadriceps, hamstrings and gastrocnemius. The quadriceps and patellar tendons meet at P. The hamstring tendons insert at H on the tibia and lie parallel to the femur. The gastrocnemius arises at G on the posterior femur. Near extension (a) it wraps around the condyle. It inserts into the heel (below the diagram); near extension (a) it wraps around the back of the tibial plateau, at J. The lever-arms of the tendons about the flexion axis are shown as  $b_q$ ,  $b_t$ ,  $b_h$  and  $b_g$  in (b).

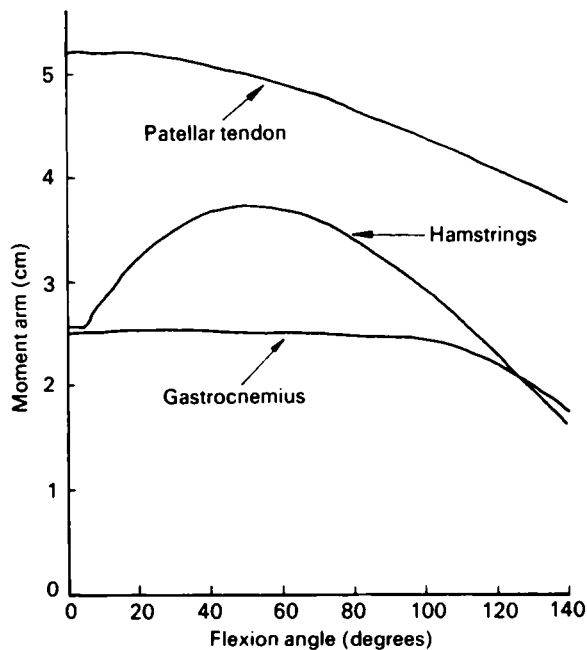


Fig. 4

Calculated lever-arm lengths of the patellar and hamstring tendons and the gastrocnemius about the flexion axis of the knee, plotted against flexion angle.

from the geometrical model and are plotted against flexion angle in Figure 4. The lever-arm of the patellar tendon is longer than that of the hamstrings over the whole range of movement, and the lever-arm of the hamstrings is longer than that of the gastrocnemius. Each varies with flexion because the directions of the tendons change and the flexion axis moves. We have verified these calculated lengths in the laboratory (O'Connor 1990a) and their general pattern agrees with deductions made from EMG signals *in vivo* by Solomonow et al (1987).

### SELF-EQUILIBRATING FORCES

A self-equilibrating system of forces is one with zero resultant force and zero resultant moment.

**Ligament and contact forces.** Consider the case of an anterior cruciate ligament graft or prosthesis which has been implanted with some initial tension. The tensile force exerted by the ligament can be resolved into two components, one parallel to the tibial plateau and one at right angles to it. The component of force parallel to the tibial plateau tends to pull the tibia backwards and must be balanced by a corresponding component of force in the posterior cruciate, pulling the tibia forwards. Initial tension in the anterior cruciate ligament therefore also induces tension in the posterior cruciate.

The components of the forces in both ligaments normal to the tibial plateau pull the tibia towards the femur and their sum must be balanced by the compressive tibiofemoral contact force. Since all three forces pass

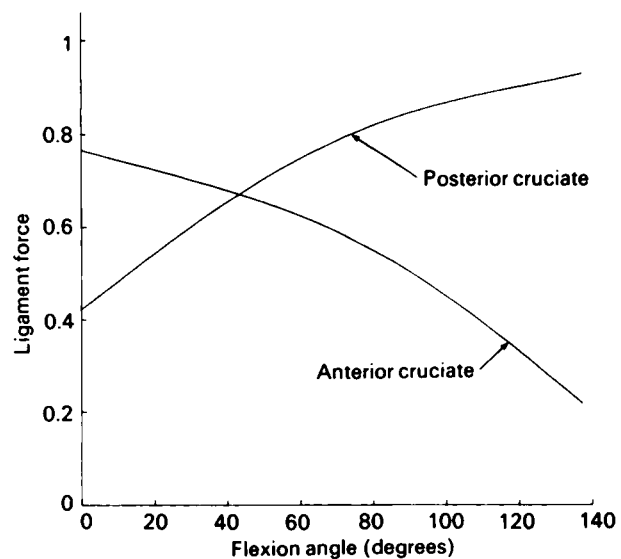


Fig. 5

Self-equilibrating ligament and contact forces. Values of the forces in the anterior and posterior cruciate ligaments, divided by the value of the tibiofemoral contact force, plotted against flexion angle.

through the flexion axis, they have no moment about that axis and can exist without inducing either flexion or extension of the joint.

The two mechanical conditions are that the components of the ligament forces parallel to the plateau must balance each other and that the sum of their components perpendicular to the plateau must equal the contact force. Both determine the *relative* values of these forces, that is the values of two of the forces as proportions of the third. The *absolute* values of the forces are determined, however, not by mechanics, but by the surgeon who implanted the graft and decided upon its initial tension.

From the cruciate linkage model we can calculate the self-equilibrating forces in the anterior and posterior cruciate ligaments as a proportion of the tibiofemoral contact force, and these are plotted against flexion angle in Figure 5. The ligament forces vary relative to each other over the flexion range because the inclination of the ligaments to the tibial plateau varies. At about 40° of flexion, the ligament forces are equal because the ligaments are equally inclined to the plateau, and the components of their forces parallel to the plateau are therefore equal and opposite. With increasing flexion, the anterior cruciate force decreases and the posterior cruciate force increases. With increasing extension, the anterior cruciate ligament force increases as the ligament becomes more steeply inclined to the plateau.

Figure 5 shows that if the graft tension is set at one flexion angle it will not necessarily be maintained over the flexion range. An anterior cruciate ligament graft, tensioned near extension, will slacken (relative to the posterior cruciate) as the joint is flexed: a graft tensioned in flexion will tighten (relative to the posterior cruciate) as the joint is extended.

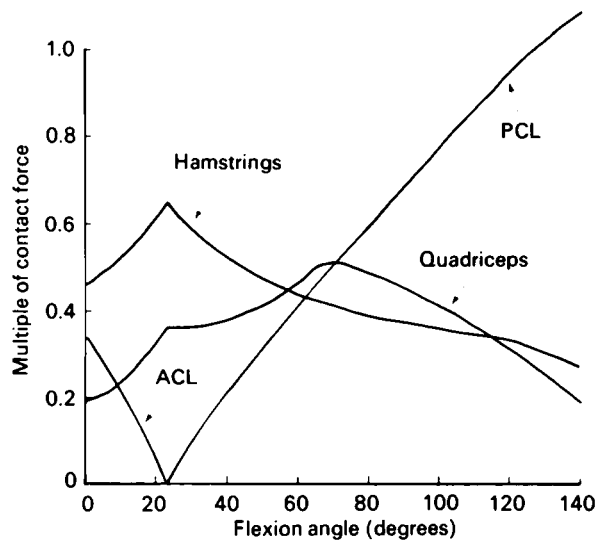


Fig. 6

Co-contraction of quadriceps and hamstrings. Values of the muscle and cruciate ligament forces, divided by the value of the tibiofemoral contact force, plotted against flexion angle.

**Muscle forces and muscle co-contraction.** When extensor and flexor muscle forces are applied simultaneously, the joint will not extend or flex if the extending and flexing moments of the muscle forces are equal. This does not necessarily mean, however, that the components of the flexor and extensor forces parallel to the tibial plateau will also be equal and opposite. Any difference has to be made up by ligament forces. Thus, when the resultant of the muscle forces parallel to the plateau acts in a forward direction on the tibia, the anterior cruciate comes under tension, and when the resultant muscle force pulls the tibia backwards, the posterior cruciate must exert a balancing forward pull. Co-contraction of the extensors and flexors at the knee will, therefore, usually load one or other of the cruciate ligaments and, as in the previous example, the sum of the components of all the soft-tissue forces perpendicular to the tibial plateau, ligamentous and muscular, must be balanced by the compressive tibiofemoral contact force.

We now have four forces transmitted across the joint – those of the extensor tendon, the flexor tendon, the tibiofemoral contact force, and the force in one or other of the cruciate ligaments. The sum of the forces parallel and perpendicular to the plateau must be zero and the moment of the forces about the flexion axis must also be zero. The absolute magnitudes of all these forces are determined by the effort put into the muscle contraction. Mechanics determines their values *relative* to one another, as in the previous example.

Similar mechanical considerations determine the relative values of other combinations of force. Patellar tendon, hamstring, gastrocnemius and tibiofemoral contact forces are another set which can equilibrate without ligament action.

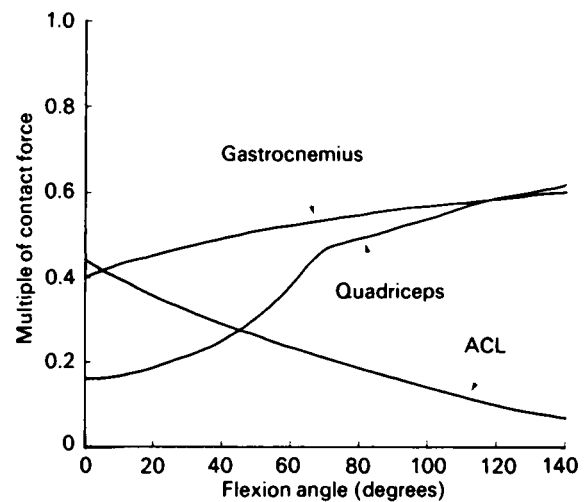


Fig. 7

Co-contraction of quadriceps and gastrocnemius. Values of the muscle and cruciate ligament forces, divided by the value of the tibiofemoral contact force, plotted against flexion angle.

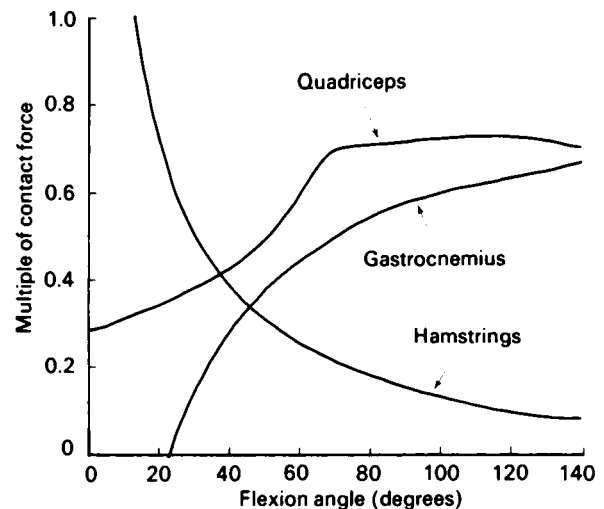


Fig. 8

Co-contraction of quadriceps, hamstrings and gastrocnemius, with zero ligament forces. Values of the muscle forces, divided by the value of the tibiofemoral contact force, plotted against flexion angle. Below 22°, the gastrocnemius force would have to be compressive. Equilibrium in this flexion range is therefore not possible without ligament forces.

In both examples, the quadriceps force can be found from the patellar tendon force by considering the mechanics of the patellofemoral joint (O'Connor et al 1990b).

#### CALCULATION OF MUSCLE FORCES

The relative magnitudes of the forces were calculated from the knee model (Figs 6 to 8) presenting the muscle and ligament forces as proportions of the tibiofemoral contact force and plotting them against the flexion angle.

The forces vary with flexion because of the variation in the lengths of the lever-arms of the muscles and because of the changing directions of the muscle and ligament forces. For the present calculations, the values of the parameters of the model were those given by O'Connor et al (1990b).

**Quadriceps and hamstrings.** Figure 6 shows how the forces vary with flexion angle when the quadriceps and hamstring muscles contract simultaneously.

Near extension, the component of the muscle forces parallel to the tibial plateau tends to pull the tibia forwards and is balanced by a (relatively small) force in the anterior cruciate ligament. When the knee is flexed beyond about 20°, the backward pull of the hamstrings dominates the forward pull of the patellar tendon and a contribution of force from the posterior cruciate ligament is required. There is a *critical flexion angle*, 22°, at which the components of the two muscle forces parallel to the plateau exactly balance each other and no ligament forces are required.

At more than 125° of flexion, a posterior cruciate ligament force *larger* than the contact force is required; the force ratio is greater than unity. This is because, in the highly flexed joint, the hamstrings force pulls the tibia distally as well as posteriorly (Fig. 3c), and the sum of the upward components of the forces in the patellar tendon and the posterior cruciate ligament now have to balance not only the downward push of the contact force but also the downward pull of hamstrings.

Although the three conditions of mechanics are not sufficient to determine the absolute magnitudes of the forces during muscle co-contraction, they can define the range of flexion over which each of the ligaments is loaded. If simultaneous quadriceps and hamstrings contractions are used for early rehabilitation, with the object of protecting an injured anterior cruciate ligament, they should be performed only with the knee flexed more than the critical angle of 22°. They should probably be avoided altogether if there is need to protect a repaired or partially injured posterior cruciate ligament.

**Quadriceps and gastrocnemius.** The results are presented in Figure 7 for simultaneous contraction of the quadriceps and gastrocnemius. The combined pull of the two muscles in a plane parallel to the tibial plateau is always directed forwards, requiring a contribution from the anterior cruciate ligament over the entire flexion range. As the knee is flexed, the ligament comes to lie more closely along the plateau and the patellar tendon more nearly perpendicular to the plateau (Fig. 3c). For both reasons, the force required in the anterior cruciate ligament decreases.

Co-contraction of quadriceps and gastrocnemius is therefore undesirable if the anterior cruciate ligament needs to be protected. It is, however, the ideal combination for early rehabilitation of a repaired posterior cruciate.

**Quadriceps, hamstrings and gastrocnemius.** Figure 8 shows

the calculated values of the force ratios when all three muscle groups act simultaneously. This is the only combination in which the anterior and the posterior cruciates can both remain unloaded throughout most of the range of movement. Only near extension, when all three muscles pull the tibia forwards (Fig. 3a), is equilibrium impossible without ligament forces.

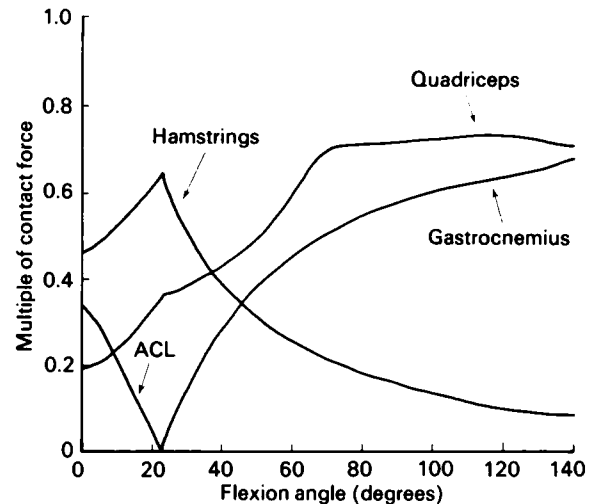


Fig. 9

Combination of co-contractions which minimise the ligament forces. Between extension and 22° of flexion, quadriceps/hamstrings give smaller anterior cruciate ligament forces than quadriceps/gastrocnemius. Above 22°, quadriceps/hamstrings/gastrocnemius co-contractions can completely protect the ligaments.

**Minimum ligament forces.** It is now possible to amalgamate the above deductions to define that combination of muscle forces which can best minimise the cruciate ligament forces in all positions of the joint (Fig. 9).

- 1) Near extension, some tension in the anterior cruciate ligament is unavoidable. If the hamstrings are employed as the knee flexor, the force in the anterior cruciate is less than if the gastrocnemius is used (Figs 6 and 7).
- 2) When the knee is flexed beyond the 22° critical flexion angle, the three muscles, acting together, can obviate the need for tension in either cruciate.
- 3) At the critical flexion angle, the quadriceps and hamstrings, acting together, can satisfy the requirements of mechanics with neither ligament nor gastrocnemius action.

## DISCUSSION

**Muscle co-contraction can unload the ligaments.** The results of the calculations suggest that, in the appropriate flexion range, muscle force can be applied without loading the cruciate ligaments. The appropriate range for each ligament depends on how the direction of the ligament varies with flexion and on the choice of flexor antagonist. Hamstrings action can protect the anterior

cruciate over most of the flexion range, except near extension; gastrocnemius action can protect the posterior cruciate over the entire flexion range. In both cases, the relative values of the flexor and patellar tendon forces are inversely proportional to the lengths of their lever-arms about the flexion axis, but the relative values of the flexor and quadriceps forces are not. The quadriceps and patellar tendon forces are not equal nor in a constant proportion to each other over the flexion range because the angle between their lines of action is not equally bisected by the line of action of the patellofemoral force (O'Connor et al 1990b). When both flexors are used simultaneously against the quadriceps, they can unload both the cruciates; except near full extension.

Although the calculations have assumed that no flexion or extension of the knee occurred as a result of the co-contraction, the conclusions should remain valid during slow movements so that remobilisation of the joint over the appropriate flexion range can safely be attempted.

Whether or not it is possible to teach patients to apply the appropriate levels of muscle forces is not a question that can be answered in terms of engineering mechanics.

**Effects of external load.** Exactly the same considerations as those of the present analysis can be used to determine the response at the joint if external loads are applied to the limb. If the flexing or extending effect of the applied load is balanced by force in only one muscle group, the values of the muscle and contact forces and the force in one or the other cruciate ligament can be obtained by a similar analysis of the model (O'Connor et al 1988, 1990b) and the range of flexion over which each of the cruciate ligaments is loaded can be determined. For instance, when a weight attached to the lower tibia is lifted by quadriceps action, the anterior cruciate ligament comes under tension, from full extension to about 70° of flexion, and the posterior cruciate ligament is loaded at higher flexion angles. This is the theoretical basis of using extension blocks with quadriceps strengthening exercises such as deep squats or pedalling a low-saddle bicycle during early rehabilitation after the reconstruction of the anterior cruciate ligament (Daniel and Stone 1990).

**Limitations of this analysis.** The calculations suggest general principles for the protection of knee ligaments after injury, but the direct application of the quantitative results requires further study. Our model of the knee is two-dimensional. Within that two-dimensional context, the ligaments are considered to be inextensible and the articular surfaces to be uncompressible. The contribution of the collateral ligaments has been ignored. These factors limit the applicability of the quantitative results. Preliminary studies of the effects of ligament elasticity (FitzPatrick and O'Connor 1989; O'Connor and Zavatsky 1990) have shown that stretching of a cruciate ligament decreases its inclination to the tibial plateau and therefore reduces the ligament force necessary to provide a given

component parallel to the plateau. Taking account of ligament elasticity also allows an estimate of the contribution of the collateral ligaments in resisting anteroposterior translation of the tibia on the femur, and thereby reducing the contributions of the cruciate ligaments. For both these reasons, the estimates of the cruciate ligament force in Figures 6 and 7 are likely to be too large. The laxity of the joint due to ligament elasticity would also slightly alter the directions of the muscle tendons and their anteroposterior components, thereby reducing the values of the ligament forces. The model clearly does not account for the effects of rotation about the long axis of the tibia or the separate contributions of the medial and lateral parts of the hamstrings and gastrocnemius.

The values of the ligament forces are very sensitive to the choice of model parameters. Near extension, the anterior cruciate ligament is most steeply inclined to the tibial plateau; in full flexion, the posterior cruciate is most steeply inclined. Although small changes in the model's parameters make only small differences to these angles, they have a disproportionate effect on the magnitude of the calculated ligament forces. This is because the value of the ligament force depends on that of its horizontal component and therefore on the cosine of the angle between the ligament and the tibial plateau. For example, since  $\cos 85^\circ$  divided by  $\cos 89^\circ = 5.0$ , an error of 4° in the estimate of ligament angles in the extreme positions can lead to very large errors in the estimates of the ligament forces necessary to provide a given component of force parallel to the tibial plateau. By the same argument, ligament grafts or prostheses which are implanted so that, in some positions, they are steeply inclined to the tibial plateau are likely to be subject to large forces by muscle action in those positions.

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