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Lines of action and moment arms of the major force-carrying structures crossing the human knee joint

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ABSTRACT

The purpose of this study was to obtain lines of action and moment arms in the sagittal plane of the major force-carrying structures crossing the knee joint. The muscles and ligaments studied were the quadriceps, biceps femoris, semimembranosus, and semitendinosus muscles and the anterior and posterior cruciate and medial and lateral collateral ligaments. All lines of action and moment arms of the structures of interest were determined as a function of knee joint angles and were expressed using polynomial regression equations. This representation of the results allows for easy application of the findings to musculoskeletal models of the human knee joint.

INTRODUCTION

Forces in biological structures crossing joints have been determined in biomechanical studies to answer 2 basic questions: first to estimate individual muscular forces, and so study the mechanisms of movement control (Pedotti et al. 1978; Crowninshield & Brand, 1981; Dul et al. 1984; Herzog, 1987), and secondly to determine stress histories of joint structures for the purpose of studying joint diseases, reconstructive surgery and the design of artificial implants (Paul, 1965; Seireg & Arvikar, 1973; An et al. 1989). For both types of study it is necessary that the musculoskeletal system is modelled appropriately. Most importantly, lines of action and moment arms of the force-carrying structures crossing the joint of interest need to be known. When trying to find such data for the human knee joint, 2 basic problems were encountered.

The first problem was associated with the fact that most studies describing lines of action and/or moment arms of structures crossing the knee joint provide these properties for isolated or selected structures, thus only presenting part of the information required. For example, van Eijden et al. (1985, 1986) concentrated exclusively on the description of lines of action of the patellar and quadriceps tendons as a function of knee joint angle. Also, Spoor & van Leeuwen (1992) used 2 elegant techniques (MRI and tendon travel) to establish moment arms of all major muscles crossing the knee joint; however, corresponding information from ligaments or data on lines of action of the muscles were not determined. Contrary to the above studies, Moeinzadeh et al. (1983) concentrated on knee joint ligaments. They determined lines of action and lengths of the collateral and cruciate ligaments to calculate forces in these structures as a function of knee joint angle, but no data were provided for muscles.

The second problem that was encountered was that in many instances, lines of action are given in terms of coordinates of origin and insertion in different bone embedded reference systems (e.g. Moeinzadeh et al. 1983) which makes it difficult to derive corresponding moment arms and lines of action for the structures of interest for general positions of the involved joints.

The purpose of this study was to obtain lines of action and moment arms in the sagittal plane for the major force-carrying structures crossing the human knee joint. In order to make these data useful for immediate application, all lines of action and moment arms were approximated using stepwise forward regression and were expressed in terms of the knee joint angle exclusively. The force-carrying structures deemed essential were the quadriceps and hamstring muscles, the 2 cruciate and the 2 collateral ligaments.

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METHODS

Data collection

Data were collected from 5 cadaver specimens. In a first step, the movement of the tibia relative to the femur was assessed throughout the full range of motion for the intact knee joint. The attachment coordinates of selected ligaments and muscles were then determined on the tibia and femur. The muscles selected contained the hamstring and quadriceps femoris muscle groups. The patellar tendon was taken to represent the quadriceps femoris muscle group. The hamstring muscle group was represented by the individual hamstring muscles: semitendinosus, semimembranosus, and biceps femoris. The ligaments of interest were the anterior and posterior cruciate ligaments (ACL and PCL) and the medial and lateral collateral ligaments (MCL and LCL). For 1 out of the 5 cadavers, all measurements were performed twice to assess the reliability of the procedures employed.

Cadaver specimens

Measurements were made on 5 fresh cadavers, 3 female and 2 male, with a mean age of 79.2 y (78–82 y). Data were collected from the right leg of each cadaver except for 1 cadaver where only the left leg was available.

Movement of the tibia relative to the femur

In order to quantify movements of the tibia relative to the femur for changing knee joint angles, 3 bony landmarks on each of the femora and tibiae were chosen as reference points. The anterior femur (15 cm proximal to the superior patella) and the most prominent points on the lateral and medial femoral condyles, were chosen on the femur. The most prominent points on the tibial tuberosity and the head of the fibula and a point on the anterior tibial crest (10 cm distal to the tibial tuberosity) were chosen on the shank segment. The apex of the patella was also included with the reference landmarks to describe the path of the patellar tendon. All prominences were marked using bone pins.

In order to stabilise the knee joint during measurements, a fixture was used to hold the full intact cadaver leg in position. Measurements were taken at ~ 10° increments of the full range of knee joint motion (~ 0° = full knee extension to 130° degrees) with the body supine and the thigh fixed to a table with straps. The lower leg was strapped to the arm of the fixture with the lateral femoral condyle lined up with the centre of rotation of the fixture. For each knee joint configuration, the reference points on the femur and tibia and the apex of the patella were digitised with a 3-dimensional mechanical digitiser (Perceptor). Data were stored on a portable Compaq computer.

Ligament and muscle insertion sites

After digitisation of the reference points, the leg was removed from the fixture. The body was rolled onto its side to mark the ischial tuberosity (insertion of the hamstring muscles) with a further bone pin. With the hip joint slightly flexed, the ischial tuberosity and the 3 reference points on the femur were digitised.

Following digitisation of the bony reference points, the knee joint was carefully dissected. All attachment areas of the muscles and ligaments of interest on the tibia and femur were identified and marked using bone pins. Fibres running from the estimated centroid of the insertion areas were assumed to represent best the behaviour of the structures. For the anterior and posterior cruciate ligaments, the most anterior and posterior aspects of the insertion areas, as described by Girgis et al. (1975) were marked. Additional bony landmarks (the most anterior, posterior, medial and lateral aspects of the tibial plateau and the most prominent point on the lateral malleolus) were digitised on the tibia for defining a bone-embedded reference system. All marked points were digitised first on the femur and then on the tibia, including the original bony reference points.

Data analysis

Insertion coordinates for each knee joint configuration

Insertion points of all structures were initially obtained relative to the reference points on the femur or tibia. Movement of the tibia relative to the femur was described by these reference points. Using coordinate transformations, all attachment coordinates were subsequently expressed in terms of a bone-embedded reference frame located on the tibia.

The tibial reference system is shown in Figure 1*a*. The origin was chosen at the most lateral aspect of the tibial plateau. The z-axis (longitudinal axis) was defined by the line joining the origin and the most prominent point on the lateral malleolus, with positive being from the origin to the lateral malleolus. The y-axis was defined as the cross-product of the z-axis and the line connecting the origin with the most medial

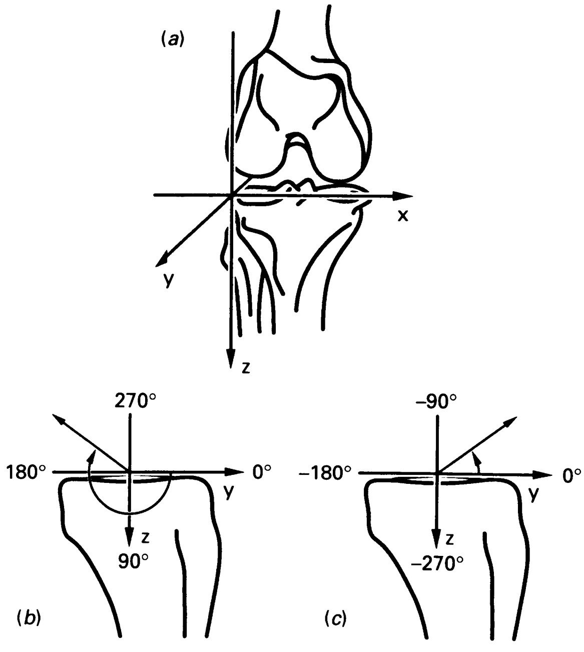


Fig. 1. (*a–c*) Bone embedded reference frame.

point of the tibial plateau. The *y*-axis was positive in the anterior direction. The 3rd axis, the *x*-axis, was obtained by completing a right-handed coordinate system, taking the cross-product of the *y*-axis and the *z*-axis. All data obtained were projected onto the *y–z* plane.

Calculation of lines of action

Sagittal plane lines of action of muscles and ligaments were calculated for each structure at each knee joint configuration. Each structure was represented by a vector directed from the insertion of the structure on the tibia to the insertion on the femur. Using the cosine function, the projected angles of the vectors in the sagittal plane were calculated. Vectors with a negative *y* component for the initial (extended) position were measured clockwise from the *y* axis and were assigned positive values (Fig. 1 *b*); vectors with a positive *y* component for the initial position were measured counter-clockwise from the *y* axis and were assigned negative values (Fig. 1 *c*).

The line of action of the anterior cruciate ligament was determined using the most anterior attachment point on tibia and femur. The line of action of the posterior cruciate ligament was determined using the midpoints of the insertion area on tibia and femur.

Calculation of moment arms

The knee joint centre was initially taken at the lateral contact point of tibia and femur as described by Nisell et al. (1986). Moment arms of each structure were obtained by calculating the perpendicular distance from the line of action of the structure about a transverse axis through the knee joint centre.

For the hamstring muscles, an average moment arm for the muscle group was calculated by taking the mean of the 3 individual muscle moment arms at each knee joint configuration. In order to assess the sensitivity of selecting a knee joint centre, moment arms were also calculated about the origin of the coordinate system (midpoint of the lateral tibial plateau) and about the lateral femoral condyle.

Regression equations

For 1 cadaver (specimen 5), a best fitting polynomial regression analysis was used to predict moment arms and lines of action of each structure as a function of knee joint angle. This particular cadaver was chosen because it was of the same sex and of similar height and weight as the subjects used in a further study (Read and Herzog, 1992). Regression analysis for the remaining specimens may be performed easily using the data presented here.

Reliability

In order to obtain an estimate of the repeatability of the entire data collection and analysis procedure, all aspects of the analysis were performed twice on 1 cadaver. Means, S.D. and maximum differences between the 2 sets of results were calculated for each parameter.

Simulation

In order to simulate a load displacing the tibia anteriorly, the tibia was displaced mathematically 7 mm in the anterior direction along the *y*-axis. This value was taken from the literature and it indicates a displacement just at the limit of injury of the ACL (Butler et al. 1980). Lines of action and moment arms were calculated using coordinates for the displaced position of the tibia. The point about which moment arm distances were calculated was also assumed to translate anteriorly by 7 mm.

RESULTS

Lines of action

Results for muscle (patellar tendon, biceps femoris,

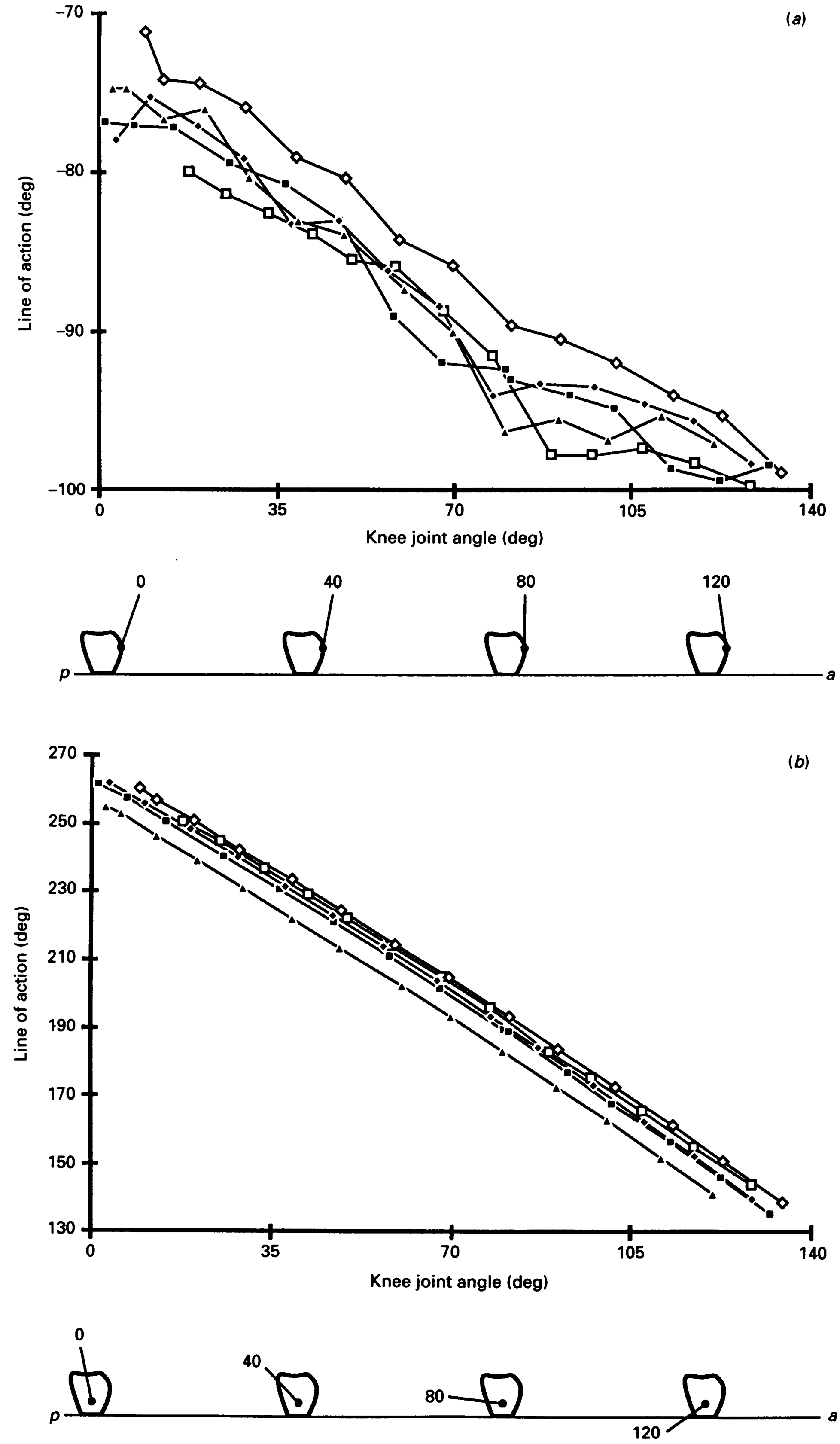


Fig. 2. For legend see opposite.

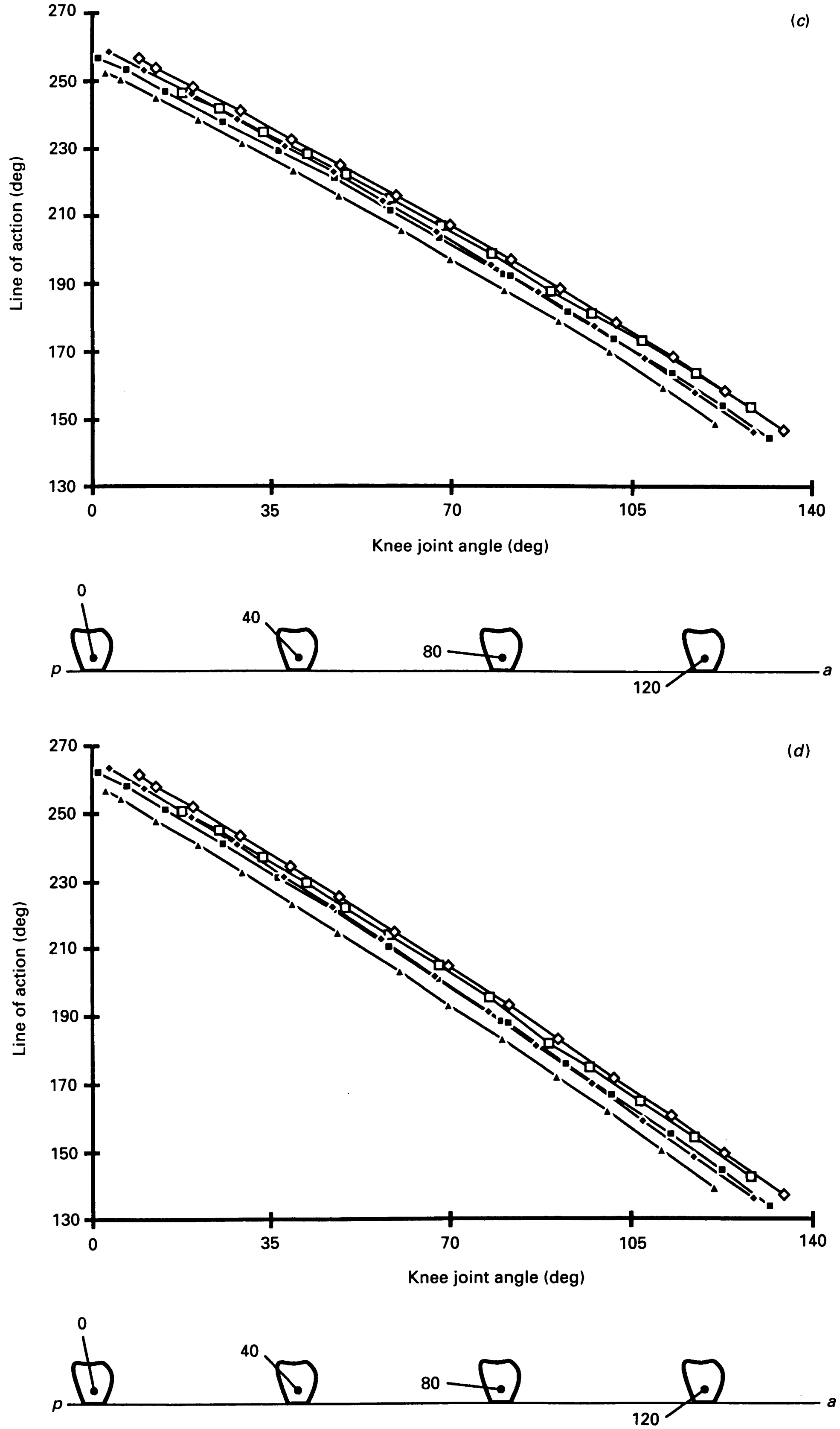


Fig. 2. Lines of action of the patellar tendon (*a*), biceps femoris (*b*), semitendinosus (*c*), and semimembranosus (*d*) as a function of knee joint angles. Lines of action are shown for all 5 cadaver specimens (1–5).

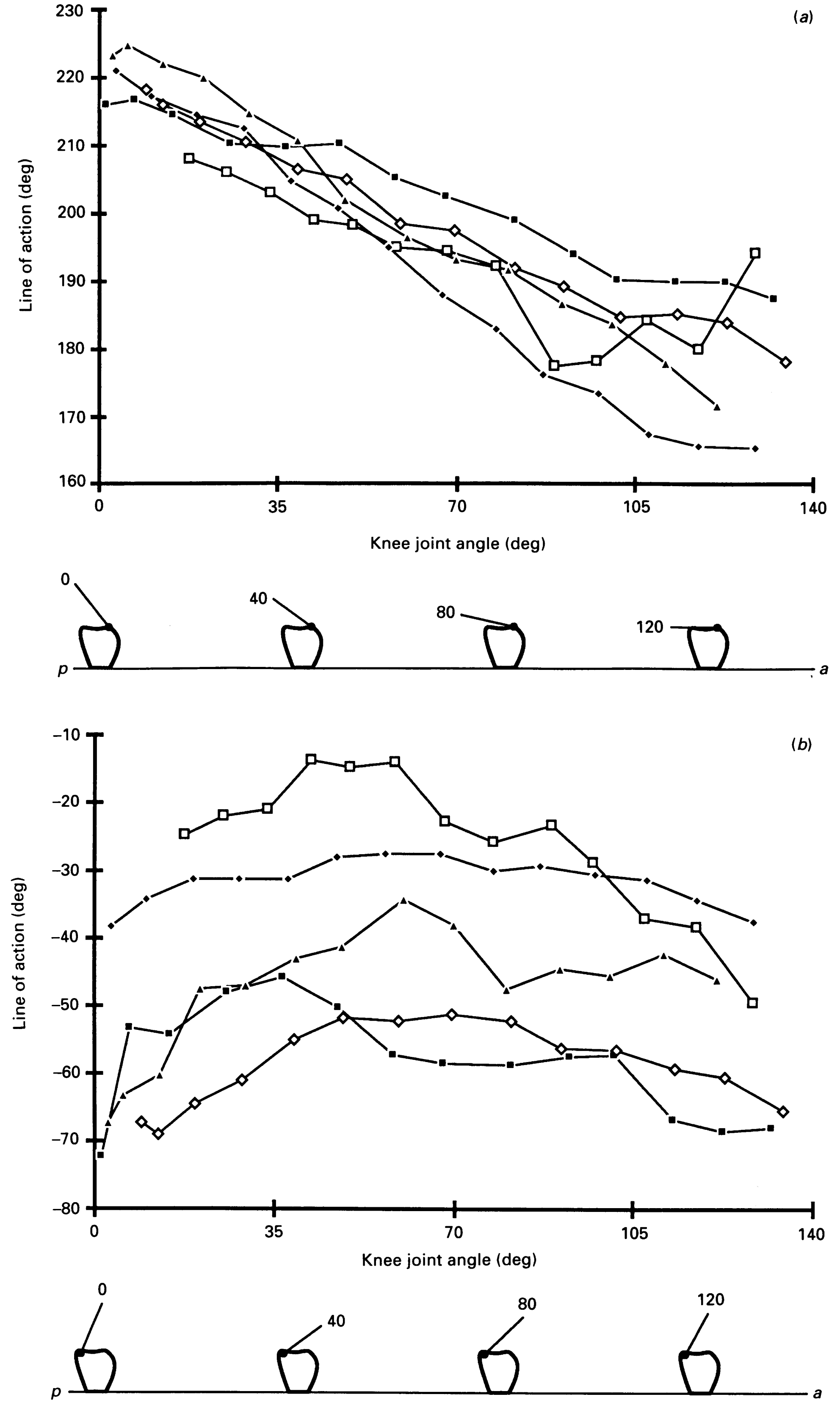


Fig. 3. For legend see opposite.

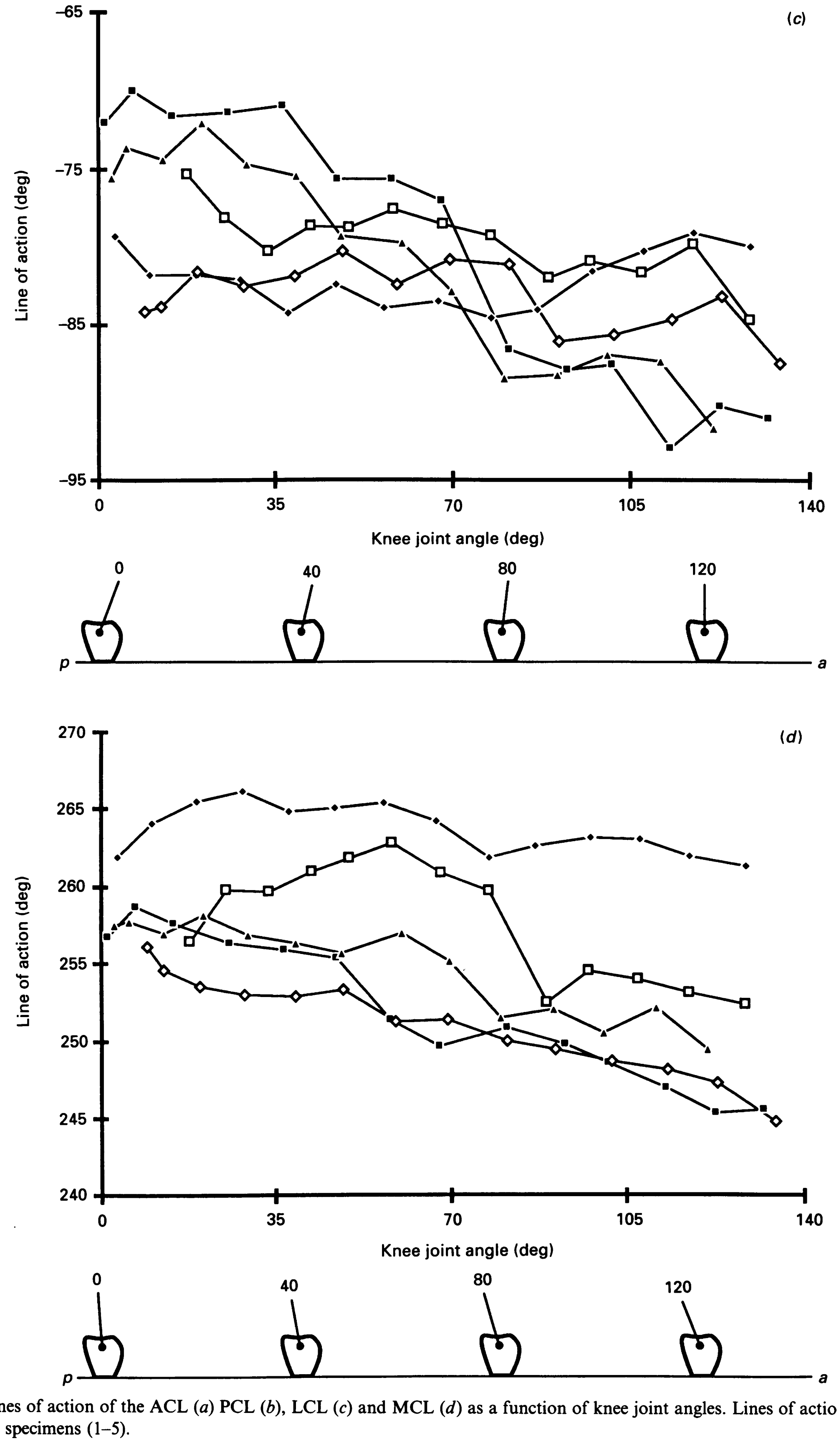


Fig. 3. Lines of action of the ACL (*a*) PCL (*b*), LCL (*c*) and MCL (*d*) as a function of knee joint angles. Lines of action are shown for all 5 cadaver specimens (1–5).

semitendinosus, semimembranosus) lines of action over the range of knee joint motion are shown in Figure 2 for all 5 cadaver specimens. Results for ligament (ACL, PCL, LCL, MCL) lines of action are given in Figure 3. In each figure, lines of action have been plotted as a function of knee joint angle. A knee joint angle of 0° represents full knee extension and angles for all lines of action are given as defined in Methods. Lateral view schematic diagrams of the tibia with the lines of action of each structure shown for selected knee joint positions (0, 40, 80, and 120°) are shown in Figure 4. For the hamstring muscles, the average line of action of the 3 muscles is shown for each knee joint angle (Fig. 4*b*).

Regression coefficients and r^2 values for predicting lines of action of each muscle and each ligament as a function of knee joint angles are given in Table 1. These coefficients were obtained from the results of cadaver 5 (the results of cadaver 5 are shown using solid triangles in each of the figures presenting raw data).

Moment arms

Results for muscle moment arms over the range of knee motion tested are shown in Figure 5*a–d* for all 5 cadavers. Average moment arms of the 3 hamstring muscles are shown in Figure 5*e*. Results for ligament moment arms are shown in Figure 6 where negative values correspond to knee extensor and positive values to knee flexor moment arms.

Regression coefficients and corresponding r^2 values for predicting moment arms of each muscle and ligament as a function of knee joint angles are given in Table 2. These coefficients were obtained using the

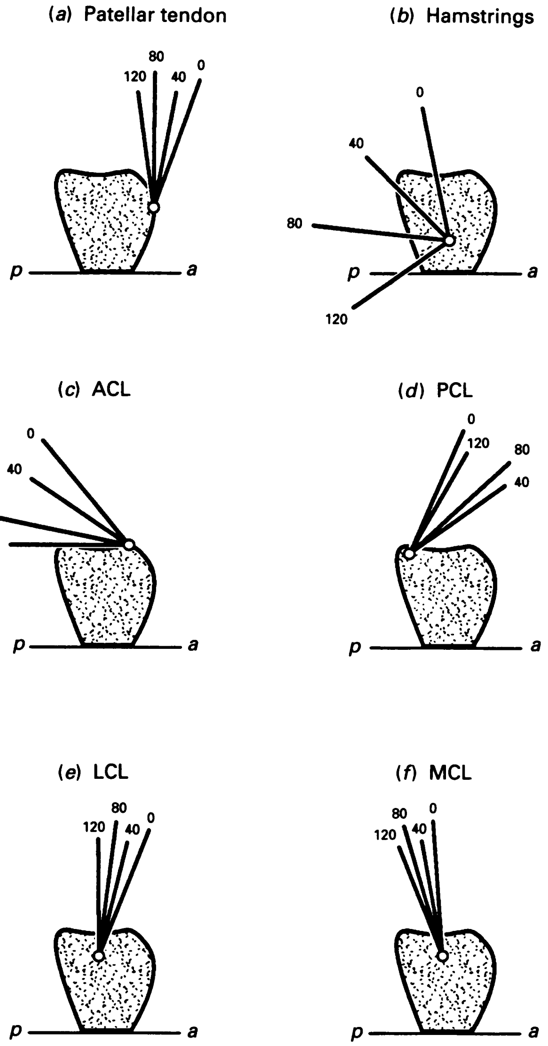


Fig. 4. (*a–f*) Lateral view schematic diagrams of the tibia showing lines of action of muscles and ligaments crossing the knee joint for selected knee joint angles. Numerical values next to the lines of action designate the corresponding knee joint angle, where 0° refers to full knee extension. *a* and *p* indicate the 'anterior' and 'posterior' aspects of the tibia, respectively.

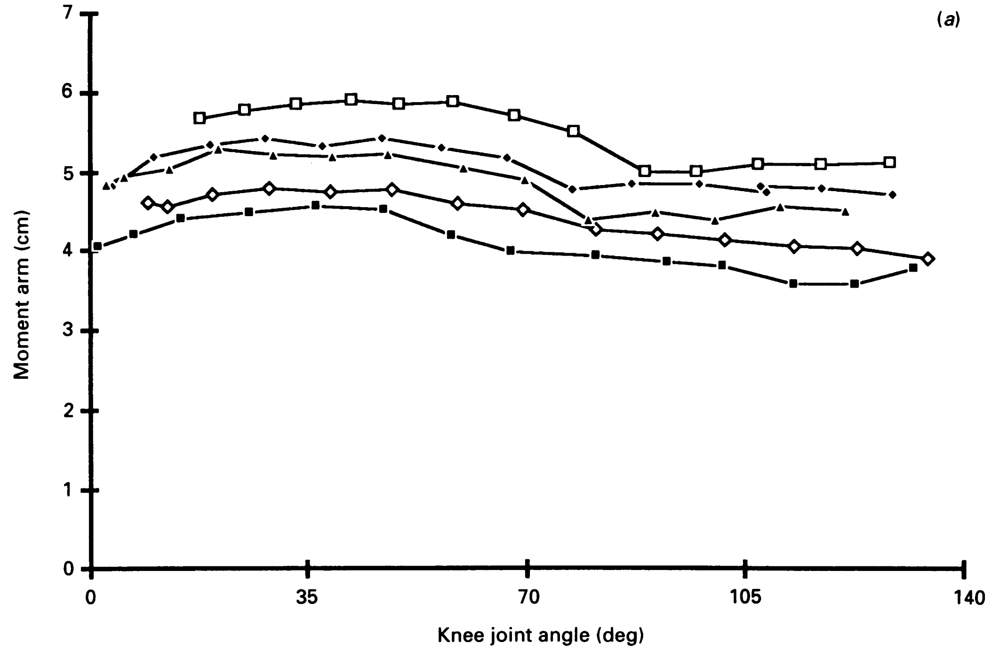
Table 1. *Regression coefficients (A0–A3) to predict lines of action of muscles and ligaments as a function of knee joint angles**

	r^2	A0	A1	A2	A3
Patellar tendon	0.98	−0.744D+02	−0.575D−01	−0.475D−02	0.309D−04
Biceps femoris	0.99	0.275D+03	−0.872D+00	−0.712D−03	0.000D+00
Semimembranosus	0.99	0.260D+03	−0.888D+00	−0.852D−03	0.000D+00
Semitendinosus	0.99	0.255D+03	−0.816D+00	0.263D−03	−0.619D−05
ACL	0.99	0.227D+03	−0.448D+00	0.000D+00	0.000D+00
PCL	0.82	−0.660D+02	0.737D+00	−0.496D−02	0.000D+00
MCL	0.85	0.259D+03	−0.699D−01	0.000D+00	0.000D+00
LCL	0.89	−0.718D+02	−0.159D+00	0.000D+00	0.000D+00

* The following equation is used:

Line of action = $A0+A1(\theta)+A2(\theta)^2+A3(\theta)^3$

The lines of action are predicted as angles in degrees as defined in the methods section. θ is the knee joint angle in degrees. The numbers are given in double precision (D) notation; thus $-0.744\ D+02 = -0.744 . 10^2 = -74.4$, etc.



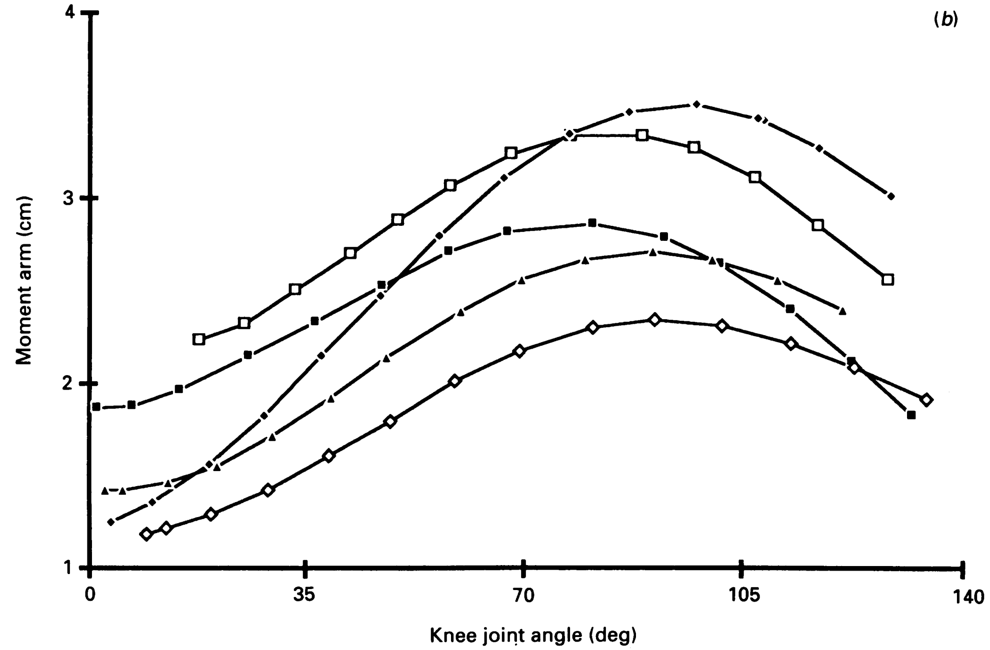


Fig. 5(*a*, *b*). For legend see page 223.

results of cadaver 5 (the results of cadaver 5 are shown using solid triangles in each of the figures presenting raw data).

Figure 7 shows the magnitudes of the moment arms for the patellar tendon and the hamstring muscle group, for the 3 definitions of knee joint 'centre': the origin of the coordinate system, the lateral femoral condyle, and the contact point. There was little change in the results for moments taken about the origin of the coordinate system (midpoint of the lateral tibial plateau) compared with the contact point. Maximum differences were approximately 0.5 cm for both the patellar tendon and the hamstring muscles. However, moment arm distances changed considerably when calculated about the lateral femoral condyle. Moment arms of the patellar tendon about the lateral femoral condyle were smaller at all knee joint angles than corresponding moment arms about the origin of the reference system and the contact point except for the most flexed knee joint position. Moment arms of the hamstring muscles about the lateral femoral condyle were consistently

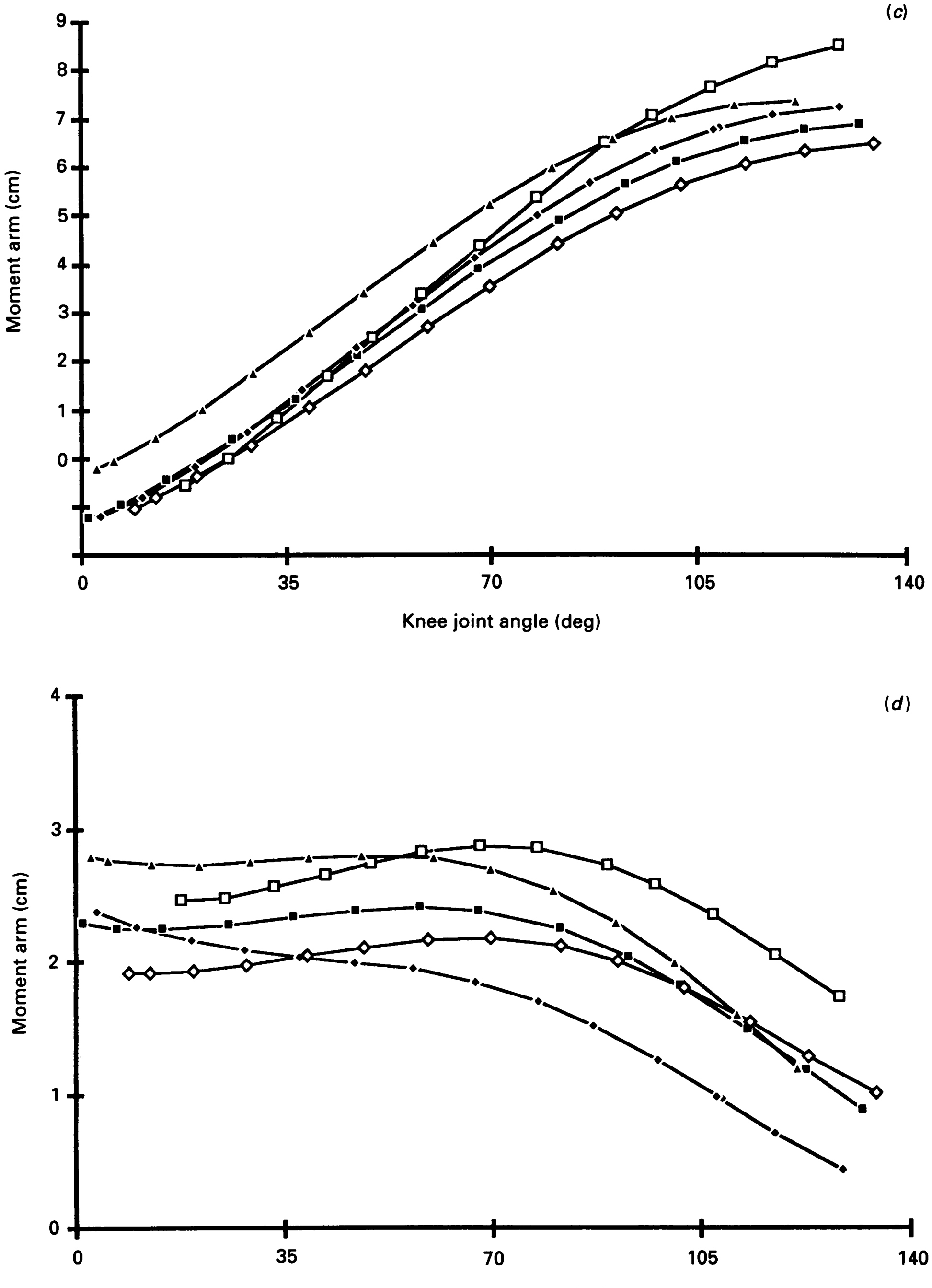


Fig. 5(*c*, *d*). For legend see opposite.

larger than corresponding moment arms about the origin and contact point.

Reliability

Table 3 shows the mean, S.D. and maximum differences between repeated measurements for cadaver 5. Values for lines of action and moment arms of muscles and ligaments as well as knee joint angles are shown. Reliability of the repeated measurements was acceptable for all structures studied.

Simulation

Figure 8 shows the changes in lines of action of the patellar tendon and the ACL from the original to the anteriorly translated (7 mm) position of the tibia.

DISCUSSION

Lines of action

Using lateral radiographs, several investigators have analysed the line of action of the patellar tendon with

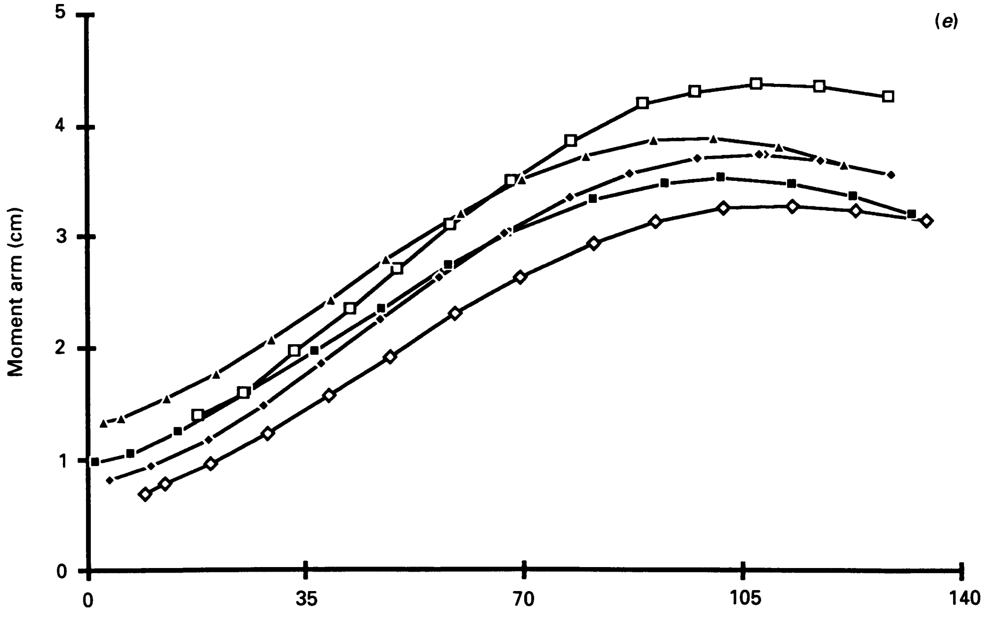


Fig. 5. Moment arms of the patellar tendon (*a*), biceps femoris (*b*), semitendinosus (*c*), semimembranosus (*d*) and average of all hamstring muscles (*e*) as a function of knee joint angles. Moment arms are shown for all 5 cadaver specimens (1–5).

respect to the longitudinal axis of the tibia over the range of knee joint flexion/extension motion. Table 4 provides a summary of the results from these studies. Besides the number of subjects studied and the range of knee joint motion tested, the maximum deviations of the line of action of the patellar tendon from the longitudinal axis of the tibia are given in the anterior and posterior direction. Also included are the knee joint angles at which the patellar tendon was parallel to the tibial axis. Although a different methodology was used in the present study, our results show a similar pattern of patellar tendon rotation through the range of motion as reported in the literature.

The knee angle at which the patellar tendon is parallel to the longitudinal axis of the tibia is important in terms of knee joint function. At extended knee joint positions, where the patellar tendon is oriented anteriorly, contraction of the quadriceps muscles tends to pull the tibia anteriorly. Likewise, at flexed knee joint positions, where the patellar tendon is oriented posteriorly, contraction of the quadriceps muscles tends to pull the tibia posteriorly. The knee joint configuration where the patellar tendon is parallel to the axis of the tibia indicates the angle of transition between anterior–posterior movement of the tibia for quadriceps contractions. Other anatomical structures crossing the knee joint must restrain the anterior or posterior pull of the knee extensor muscles. In this study, structures that were directed posteriorly throughout the range of motion and which therefore could potentially restrain anterior movements of the tibia were the ACL, MCL and the hamstring muscles. Structures that were directed anteriorly and could potentially restrain posterior tibial movements were the PCL and LCL.

Young et al. (1988) examined the movement of the tibia relative to the femur in cadavers using optical methods. With the ACL cut and force applied to the quadriceps muscle, the tibia was reported to move anteriorly up to mean knee flexion angles of 65°, but not beyond. This result agrees well with the predictions made in the present study, based on the line of action of the patellar tendon.

Recently, several in vitro studies have investigated the effects of muscular contraction on strain in the ACL. Arms et al. (1984), Renstrom et al. (1986) and Draganich & Vahey (1988, 1989) all measured strains in the ACL during simulated isometric contractions of the quadriceps muscle group. Peak strains and minimum strains were reported in the ACL at knee flexion angles ranging from 10 to 30° and 75 to 90°, respectively. A similar pattern of strain was reported by Beynnon et al. (1988) where strains were measured in vivo for active movements.

The lines of action of the 3 individual hamstring muscles were similar throughout the range of motion (Fig. 2*b*–*d*). Thus in the 2-dimensional situation it seems appropriate to group these muscles as a single functional unit, based on their lines of action. Since the line of action of all hamstring muscles was directed posteriorly, contraction of these muscles would tend to pull the tibia posteriorly. According to the lines of

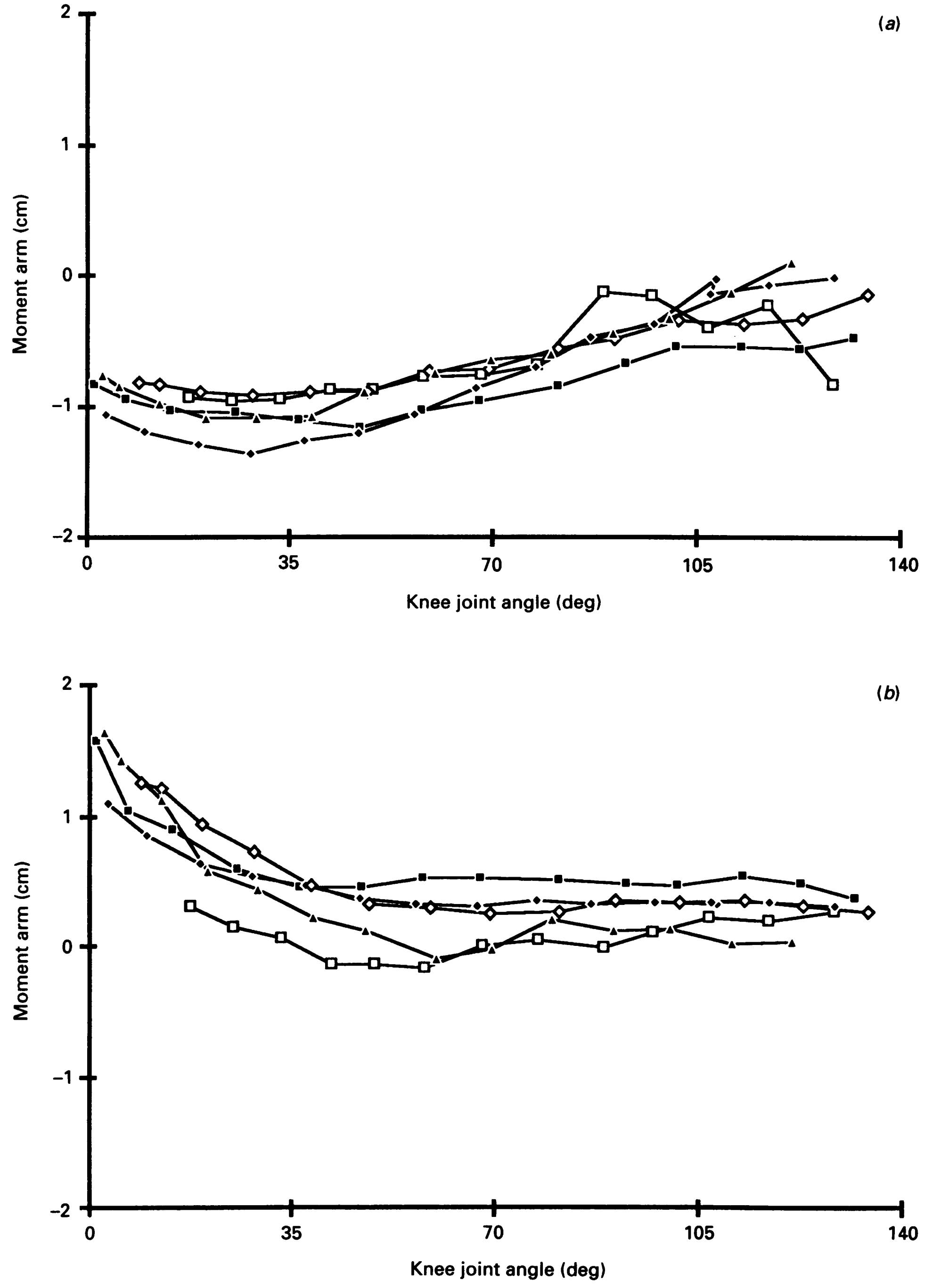


Fig. 6(*a*, *b*). For legend see opposite.

action of ligaments obtained in this study, this would tend to unload the ACL and MCL and load the PCL and LCL.

In some studies where the effect of quadriceps forces on the ACL (anteromedial aspect) was investigated, the effect of hamstring forces on the ACL was also considered. The addition of hamstring forces was found to decrease strains in the ACL at all knee joint configurations relative to passive normal strains and relative to strains measured for quadriceps forces alone (Renstrom et al. 1986; Draganich et al. 1989).

In an in vivo study, Henning et al. (1985) reported no elongation of the anteromedial ACL fibres with hamstring contraction.

Young et al. (1988) examined the ability of the hamstring muscles to recover the tibia to its normal position when being displaced by quadriceps forces in ACL deficient cadaver knees. They found that beyond 65° of flexion, no hamstring forces were required because the quadriceps muscles tended to pull the tibia posteriorly. For knee joint angles smaller than 65°, the hamstring forces required to balance a given

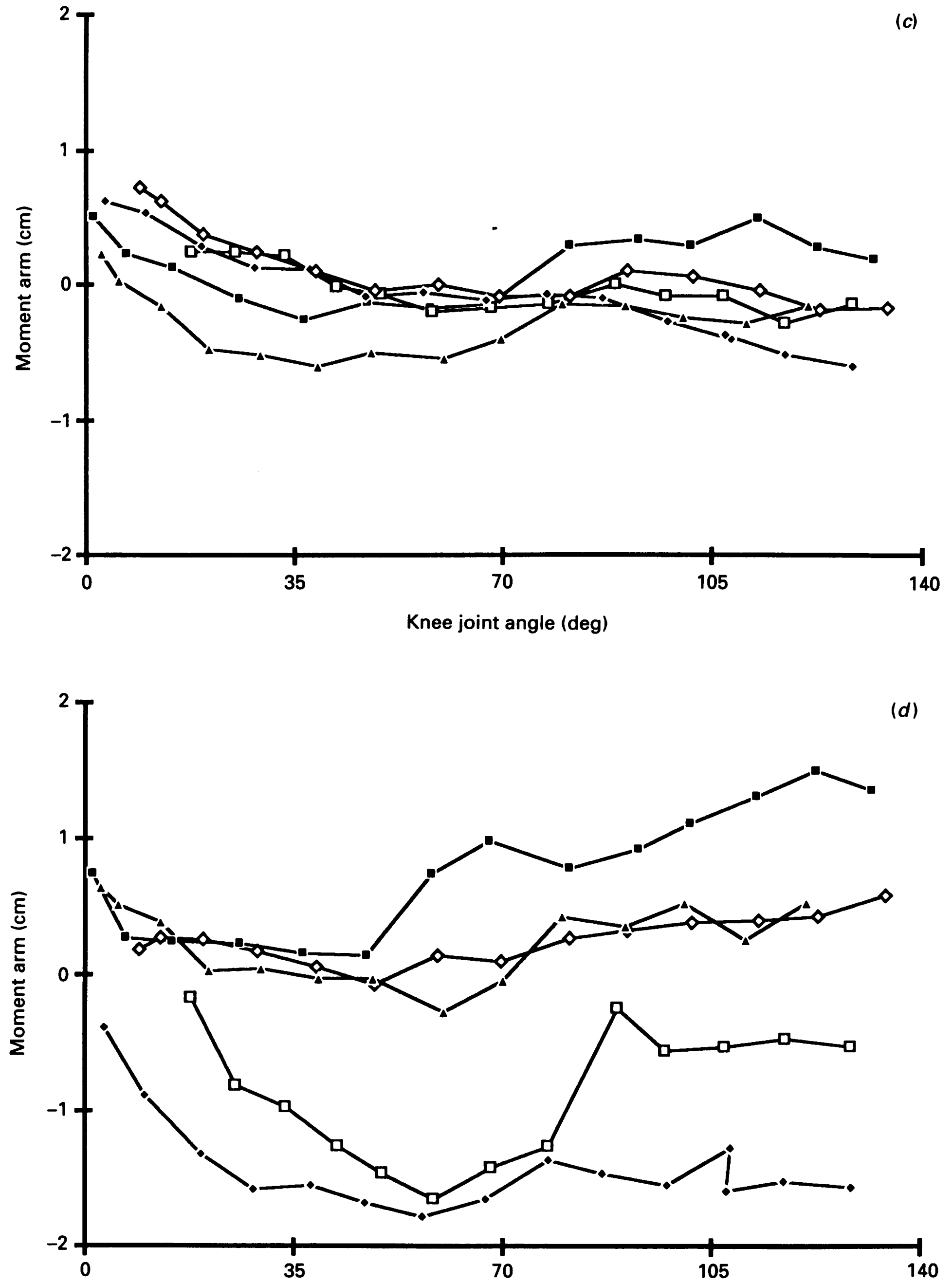


Fig. 6. Moment arms of the ACL (*a*), PCL (*b*), LCL (*c*) and MCL (*d*) as a function of knee joint angles. Moment arms are shown for all 5 cadaver specimens (1–5).

quadriceps force became larger as the knee joint was extended. This study demonstrated experimentally the decreasing posterior component and the increasing anterior component of the lines of action of hamstring and quadriceps muscles, respectively, for increasing knee joint extension. This result supports our findings (Fig. 2).

The ACL (anteromedial aspect) was directed proximally and posteriorly throughout the range of motion (Fig. 3*a*), thus restraining anterior movements of the tibia relative to the femur. This finding agrees with results reported in the literature that identify the ACL as providing the main restraint to anterior displacements of the tibia (e.g. Butler et al. 1980). Most studies examining the function of the ACL experimentally (as done here) focus on the anteromedial portion of the ACL exclusively (e.g. Kennedy et al. 1977; Ahmed et al. 1987) or the ACL as a whole ligament (e.g. Butler et al. 1980). This may result in the neglect of other possible functions of the ACL associated with its

Table 2. *Regression coefficients (B0–B4) to predict moment arms of muscles and ligaments as a function of knee joint angles**

	r^2	B0	B1	B2	B3	B4
PT	0.92	0.471D+01	0.420D−01	−0.896D−03	0.447D−05	0.000D+00
Bf	0.99	0.146D+01	−0.926D−02	0.855D−03	−0.878D−05	0.238D−07
Sm	0.99	0.284D+01	−0.161D−01	0.681D−03	−0.880D−05	0.277D−07
St	0.99	−0.411D+00	−0.586D−01	0.690D−03	−0.531D−05	0.000D+00
ACL	0.99	−0.642D+00	−0.431D−01	0.130D−02	−0.131D−04	0.475D−07
PCL	0.98	0.184D+01	−0.739D−01	0.963D−03	−0.396D−05	0.000D+00
MCL	0.51	0.586D−01	−0.167D−01	0.130D−03	−0.000D+00	0.000D+00
LCL	0.59	0.558D+00	−0.198D−01	0.171D−03	−0.000D+00	0.000D+00

* The following equation is used:

$$\text{Moment arm} = B0 + B1(\theta) + B2(\theta)^2 + B3(\theta)^3 + B4(\theta)^4$$

The moment arms are predicted in cm as defined in the methods section. θ is the knee joint angle in degrees. PT, patellar tendon; Bf, biceps femoris; Sm, semimembranosus; St, semitendinosus. The numbers are given in double precision (D) notation; thus 0.471 D+01 = $0.471 . 10^1 = 4.71$.

posterior fibres. Attempts to quantify the function of the posterior fibres of the ACL using the present methodology failed due to the inaccessibility of the posterior attachment points with the digitiser.

The PCL was directed anteriorly and proximally, thus restraining posterior movements of the tibia with respect to the femur (Fig. 3*b*). This agrees well with experimental results where the posterior cruciate ligament has been found to contribute zero or negligible restraining force to anterior movements but is the main passive structure restraining relative posterior movements of the tibia (e.g. Butler et al. 1980; Ahmed et al. 1987).

The LCL was found to have a similar orientation as the PCL (Fig. 3*c*). However, at the most flexed position, the LCL was directed slightly posteriorly in 2 cadavers. This posterior orientation was increased and occurred at a more extended knee joint position when the tibia was translated anteriorly. Thus it appears that the LCL may have different functions throughout the range of knee joint motion. Nevertheless, the orientation of this ligament does not diverge far from the vertical in either direction and its restraining force to anterior or posterior movements of the tibia relative to the femur is thus assumed to be small. This has been supported in the literature (e.g. Butler et al. 1980; Ahmed et al. 1987).

Lines of action of the MCL indicate a similar function as the anterior ACL in restraining anterior movements of the tibia (Fig. 3*d*). However, the MCL was oriented almost parallel to the longitudinal axis of the tibia for all knee joint configurations and its component in the anterior direction is small, indicating that its restraint to anterior translations of the tibia is weak. This is supported in the literature, where the MCL has been identified as a secondary restraint to anterior displacement of the tibia (e.g. Butler et al. 1980).

Moment arms

In this study, moment arm distances of the patellar tendon showed similar patterns but tended to be somewhat larger than corresponding distances determined by other researchers (Fig. 5*a*) (Spoor & van Leeuwen, 1992). The moment arm increased to a maximum value at a knee joint angle of approximately 30° and decreased with further knee flexion. Results for moment arm distances of the patellar tendon in this study indicate that the largest moments can be generated for a given force between knee joint angles of 20–65°. Other mechanical properties of muscles (e.g. force–length relations) also must be considered when predicting the potential to produce maximal moments for the quadriceps muscles.

Smidt (1973) performed one of the few studies that included an examination of hamstring moment arms. Moment arm distances were calculated as the perpendicular distance from the joint centre to the line of action of the hamstring muscles. The line of action of the hamstrings was assumed to be parallel to the longitudinal axis of the femur and the joint centre was defined using the instantaneous joint centre concept. Moment arm values from Smidt's study ranged from a minimum of 2.5 cm at full knee extension to a maximum of 4.1 cm at 45° of knee flexion. Average moment arm values for the 3 hamstring muscles grouped together in the present study were similar to those reported by Smidt (Fig. 5*e*).

Unlike the lines of action, the moment arms for the individual hamstring muscles were distinctly different (Fig. 5*b–d*). The biceps femoris moment arms

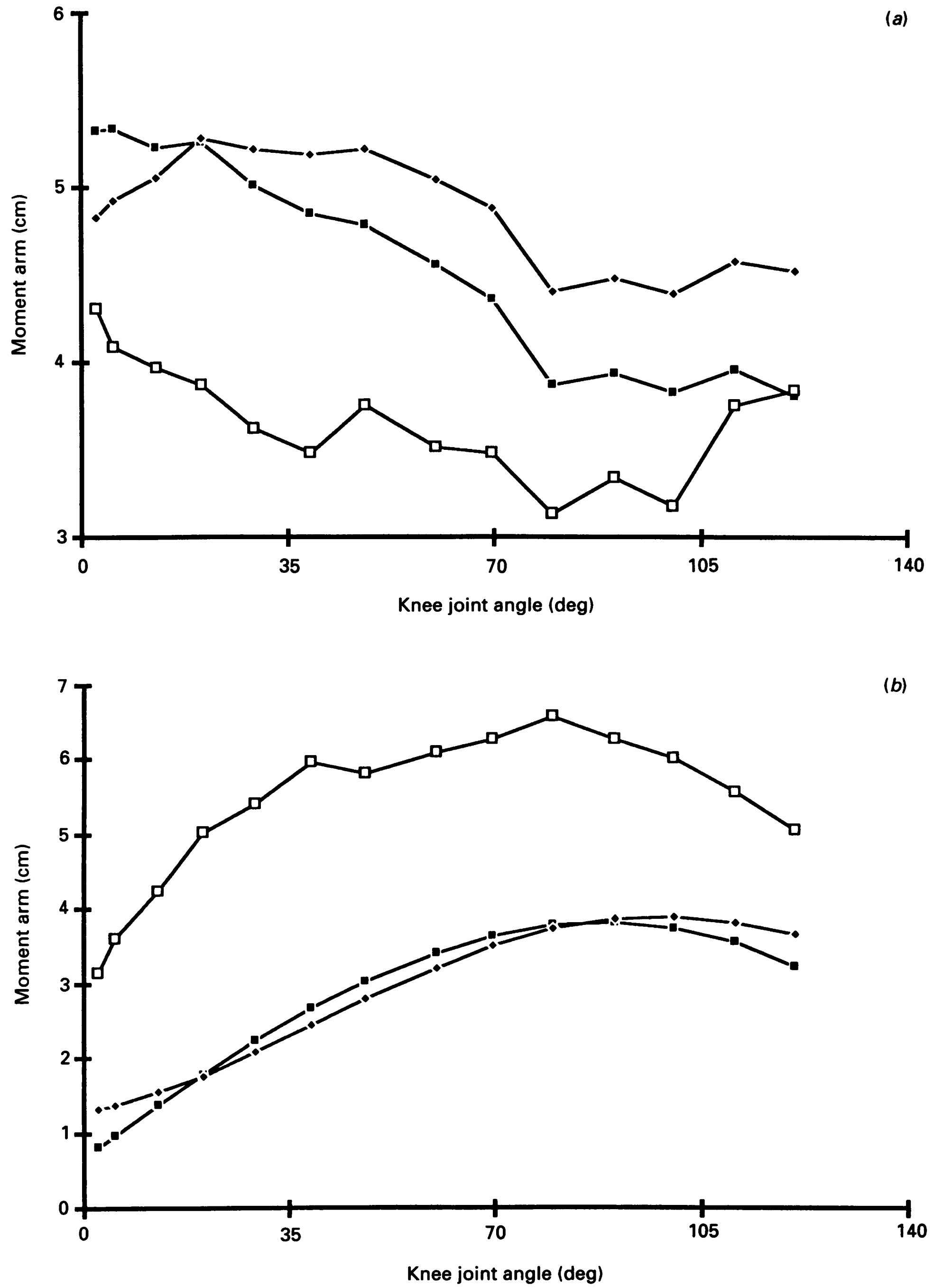


Fig. 7. Moment arms for the patellar tendon (*a*) and the average of the 3 hamstring muscles (*b*) as a function of knee joint angles using the 3 definitions of the knee joint 'centre': the origin of the reference system (Fig. 1) (■, origin), the lateral femoral condyle (□, condyle), and the contact point between tibia and femur (◆, contact).

increased through flexion to a maximum at knee angles between 75 and 100°, and then decreased slightly with further flexion (Fig. 5*b*). The semitendinosus muscles had the largest changes in moment arms for all muscles throughout the range of motion (Fig. 5*c*). All cadavers had an extensor moment arm for the semitendinosus at the most extended knee joint positions as indicated by the negative values on the graph. This result does not agree with corresponding moment arms obtained using measurements of tendon travel as a function of knee joint angles (Spoor & van Leeuwen, 1992) and may be associated with the assumption of representing semitendinosus by a straight line. With further flexion, the moment arms became flexor, and increased to a maximum at full flexion. The moment arms for the semimembranosus muscles showed little changes in moment arm distances at extended knee positions up to approximately

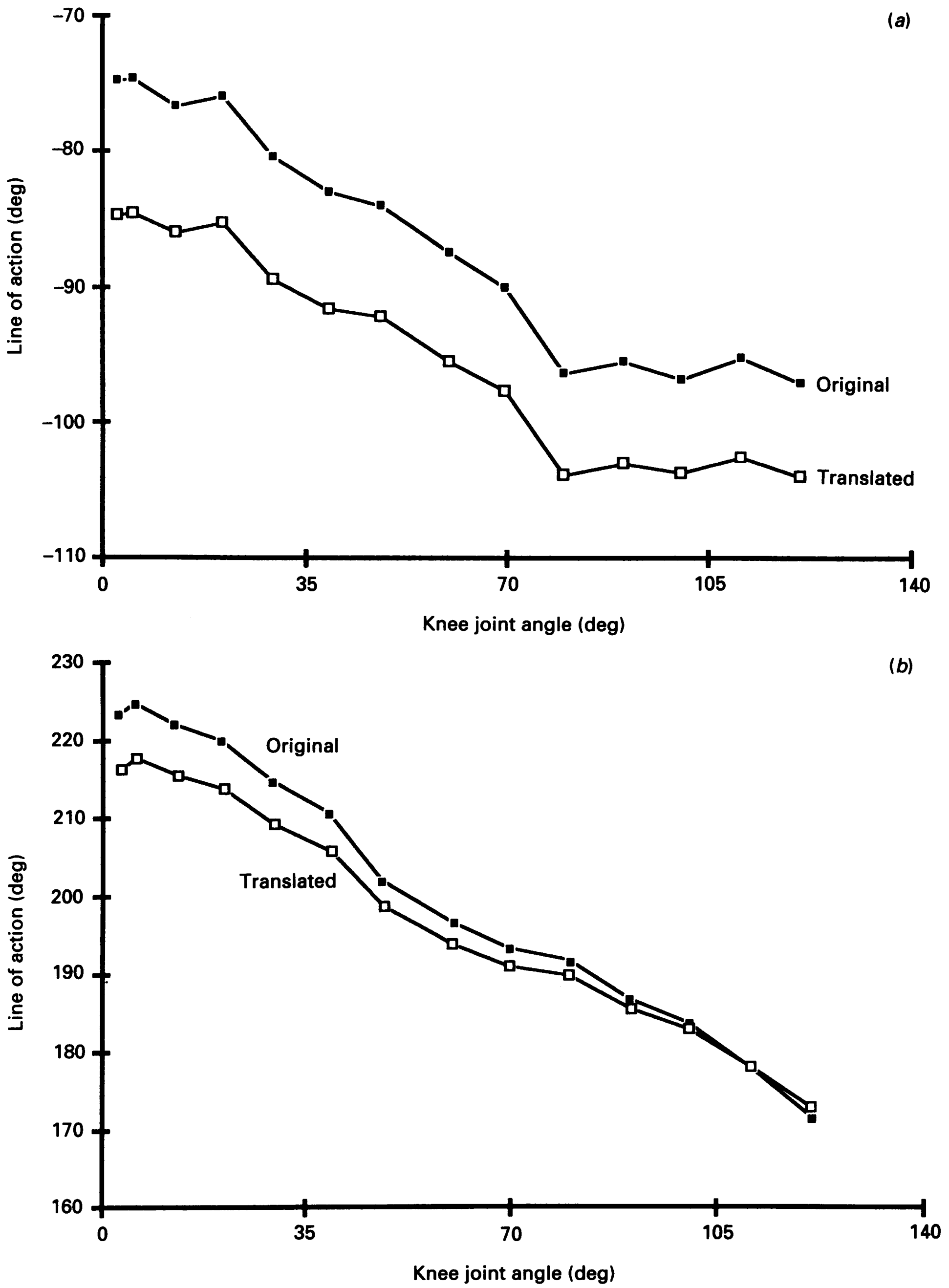


Fig. 8. Lines of action of the patellar tendon (*a*) and the ACL (*b*) as a function of knee joint angles using the original tibia position (original) and the 7 mm anteriorly translated tibia position (translated).

Table 3. *Mean, s.d. and maximal differences between repeated measurements of moment arms, lines of action and knee joint angles performed on 1 cadaver specimen*

Variable	Mean	s.d.	Maximum
Moment arms	(mm)	(mm)	(mm)
Muscles	2.5	1.1	5.2
Ligaments	2.1	1.2	7.8
Lines of action	(deg)	(deg)	(deg)
Muscles	−0.4	1.9	3.9
Ligaments	−2.5	2.7	13.0
Knee joint angle	1.3	1.8	4.1

80° of flexion (Fig. 5*d*). Beyond 80° of flexion, moment arms decreased to reach minimum values at full flexion. The average of the 3 hamstring moment arms increased in magnitude as the knee joint was flexed up to values between 100 and 120° and then tended to decrease slightly (Fig. 5*e*).

Moments generated by ligaments about a transverse axis though the knee joint are typically neglected in knee joint models, since forces and moment arms for ligaments are assumed to be smaller compared with

Table 4. *Summary of results from the literature describing the line of action of the patellar tendon*

			Patellar tendon angle		Knee angle
Author	(n)	Knee angles (deg)	Anterior (deg)	Posterior (deg)	Parallel (deg)
Nisell et al. (1986)	20	0–120	30	10	100
Van Eijden et al. (1985)	10	0–120	20	18	75 (60–80)
Van Eijden et al. (1987)	5	0–120	25	18	80 (75–85)
Buff et al. (1988)	8	0–90	11	9	60 (50–70)
Present study	5	0–130	19	10	(60–90)

corresponding values for muscles. The maximum moment arm of a ligament calculated in this study was about 1.7 cm (PCL, Fig. 6*b*), compared with maximal values of about 6 cm for the quadriceps muscles (Fig. 5*a*), and 3.5 cm, 8 cm and 3 cm for biceps femoris (Fig. 5*b*), semitendinosus (Fig. 5*c*) and semimembranosus (Fig. 5*d*), respectively.

In cadaver 5, the maximum moment arm calculated for the ACL was approximately 1.1 cm (Fig. 6*a*). Assuming a force of failure of the ACL of 2500 N (Hollis et al. 1988), the maximal moment that can be produced by the ACL is about 27.5 Nm. This is small compared with resultant knee joint moments measured for maximum isometric contractions (about 300 Nm) which are reported in the literature (Herzog et al. 1991). It therefore seems reasonable to neglect the contribution of moments due to ligamentous forces, particularly when resultant knee joint moments are high. Moreover, the direction of ligament moment arms was found to be very sensitive to changes in the definition of the knee joint centre; potential errors associated with the determination of ligamentous moments may therefore be larger than the error associated with neglecting these moments.

The definition of the knee joint centre about which moment arms of the muscles and ligaments are determined varies according to the literature source. Consequently, it is difficult to compare moment arm values between studies. Models of the knee joint that are used in whole body movement analysis often take a fixed knee joint centre (e.g. Morrison, 1969). However, the instantaneous centre of rotation of the tibia relative to the femur, which is sometimes defined as the knee joint centre, has been shown to vary as a function of knee joint configuration (Frankel et al. 1971; Smidt, 1973; Soudan et al. 1979). Furthermore, investigations on the contact point between the tibia and femur, which has also been defined as the knee joint centre, report a large posterior translation of this point as the knee joint is flexed (Walker & Hajek, 1972; Harding et al. 1977; Nisell et al. 1986).

Most often, knee joint moments have been calculated about the contact point between femur and tibia (Lindahl & Movin, 1967; Nisell et al. 1986; Van Eijden et al. 1987). Although the contact point is not the true joint centre, it is a simple and consistent definition which eliminates the moment due to joint articular contact force, since this force, by definition, passes through the contact point. In the present study, the contact point was used for the calculation of moment arms of muscles and ligaments crossing the knee joint; however, it was found that the results were sensitive to changes in the definition of the knee joint centre, particularly when the joint was defined using the lateral femoral condyle (Figs 7*a*, *b*). The instantaneous centre of rotation of the tibia relative to the femur has been found to be in the vicinity of the lateral femoral condyle, although large variations in the precise location have been reported (Frankel et al. 1971; Smidt, 1973; Soudan et al. 1979).

Ligament moment arms were extremely sensitive to changes in the definition of the knee joint centre. In many instances the function of the ligament, in terms of flexor or extensor, changed when moments were taken about the lateral femoral condyle, rather than about the origin of the coordinate system or the contact point.

Simulation

The line of action of the patellar tendon and the ACL rotated posteriorly for an anterior translation of the tibia at all knee joint positions except for the ACL at the most flexed knee joint angles (Fig. 8*b*). The angle at which the line of action of the patellar tendon became parallel to the longitudinal axis of the tibia (i.e. −90°, Fig. 8*a*) was more extended (approximately 30°) for the translated compared with that of the original position (approximately 60°). Lines of action of the hamstring muscles changed by less than 1° with anterior translation. In general, an anterior translation of the tibia tended to rotate the lines of action of all muscles and ligaments in a posterior direction.

Moment arms of ligaments were slightly more sensitive than moment arms of muscles to anterior translations of the tibia. The maximum difference in moment arm for the anterior ACL was 3.6 mm.

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