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The fibre bundle anatomy of human cruciate ligaments

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ABSTRACT

The cruciate ligaments of the knee consist of numerous fascicles, groups of which comprise fibre bundles. The stabilising function of these ligaments is established by changes in the lengths and orientations of the fascicles. Understanding the function of knee ligaments thus requires an understanding of their 3-dimensional fascicle architecture. Hitherto, the cruciate ligaments have been considered functionally as single-dimensional 'ropes' or, at the most, as consisting of anterior and posterior parts. It is evident from the appearance of these ligamentous structures, however, that fascicles in more than 2 directions are present. This study investigated how many and which fibre bundles are minimally needed to preserve the main fascicle directions in the ligaments. An anatomical analysis of the cruciate ligaments was performed using a 3-dimensional measuring device. Three anterior and 3 posterior cruciate ligaments were isolated and their fascicles measured. Based on the courses of the fascicles, fibre bundles were defined, dissected bluntly, and their corresponding insertion sites measured. Finally, the insertion sites of the bundles were connected into straight-line representations by a computer and transformed to the anatomical position of the knee, so as to be useful for functional analyses of the ligaments. It was found that 6–10 bundles are sufficient to represent the main fascicle directions of the ligaments. Although the number of fibre bundles is not identical for all ligaments, the femur and the tibia are connected in a consistent way by these bundles. Even the ways in which the fibre bundles change their interrelationship from the femoral to the tibial insertion sites are comparable. The results serve as a detailed anatomical basis for functional analyses of the cruciate ligaments.

Key words: Knee joint; cruciate ligaments; fibre bundles; human.

INTRODUCTION

The cruciate ligaments consist of several macroscopically visible fascicles. Because of the variable orientation of these fascicles, the cruciate ligaments are capable of stabilising the knee in several directions during knee motion. In order to understand this complex functional behaviour, a precise and complete description of the fascicles is required with respect to their spatial orientation and their femoral and tibial insertion sites at different knee positions.

Most authors have described the cruciate ligaments as consisting of 2 or 3 anatomically distinct groups of fascicles or fibre bundles (Girgis et al. 1975; Norwood & Cross, 1979; van Dijk, 1983; Buck, 1985; Lembo et al. 1985; Amis & Dawkins, 1991). Other authors have considered the cruciate ligaments as assemblies of fascicles, which cannot really be grouped into anatomically distinct bundles (Dorlot et al. 1983; Odensten & Gillquist, 1985; Fuss, 1989). There is agreement among authors, however, that these fascicles are not uniformly tensed during knee motions. To study this complex functional behaviour of the ligaments, a division of the cruciate ligaments into fibre bundles is necessary, whether anatomically distinct bundles are present or not. For this purpose, variations in lengths of the different fibre bundles during knee motions have been determined. Fuss

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(1989), for example, split the ligaments into artificial bundles of fibres and obtained approximations of the variations in distances between their insertion sites during knee flexion using 2-D radiography. Others derived these so-called 'length patterns' from 3-D measurements of the insertion sites of bundles (Van Dijk, 1983; Odensten & Gillquist, 1985; Butler, 1989; Amis & Dawkins, 1991; Blankevoort et al. 1991; Hollis et al. 1991).

Commonly, these length patterns were based on changes in distances between the insertion sites of 2 or 3 distinct fibre bundles (Wang et al. 1973; Trent et al. 1976; Van Dijk, 1983; Lembo et al. 1985; Blankevoort et al. 1991). It is, however, questionable whether the function of the cruciate ligaments can be described by a change in length of only a few fibre bundles. It has been shown that a ligament represented by 2 fibre bundles is not capable of stabilising the knee joint in all positions of the knee (Blankevoort, 1991). Furthermore, from the appearance of the cruciate ligaments it is clear that fibre bundles in several directions are present. A more detailed and precise description of the insertion sites of the ligaments is thus required.

The aim of the present study was to determine how many and which fibre bundles are minimally needed to preserve the main fascicle directions in the cruciate ligaments. For this purpose, the courses and insertion sites of several fibre bundles of these ligaments were assessed using a 3-dimensional measuring device. Secondly, based on the recorded anatomy, line representations were obtained by connecting corresponding insertion sites. Finally, these representations were presented in an easily recognisable anatomical position of the knee, i.e. the extended position. These representations should provide a detailed basis for functional analyses of the cruciate ligaments.

MATERIALS AND METHODS

To quantify the anatomical courses of the fibre bundles as well as their insertion sites, a 3-dimensional digitiser was used (Fig. 1, 3Space Isotrak, Polhemus Navigation Sciences, Colchester, VT, USA). The digitiser consists of a sensor receiving the electromagnetic signals which a source transmits. With the digitiser the spatial positions of the tip of a stylus, rigidly fixed to the sensor, can be measured with an accuracy of 0.35 mm (Sidles et al. 1988).

The measurements were performed on the anterior (ACL) and posterior cruciate (PCL) ligaments of 3

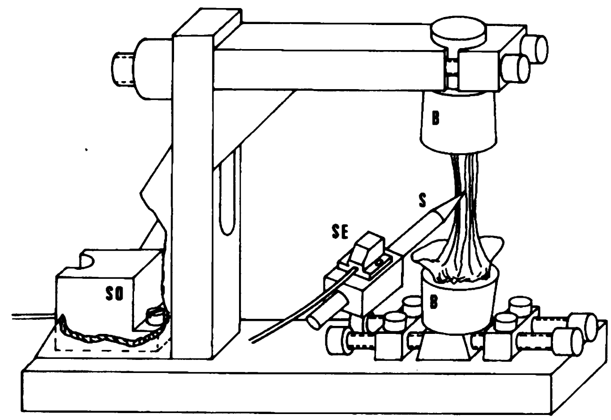

Fig. 1. The perspex support in which a ligament is mounted for the measurement of its fibre bundle geometry with the aid of 3Space Isotrak. SO, source; SE, sensor; B, bone cement; S, stylus.

knee-joint specimens from subjects aged 71, 63 and 89 y, respectively. These joints were freshly frozen in plastic bags at −20 °C and slowly thawed at room temperature at the time of usage. This method of preservation did not markedly affect the arrangement of collagen fibrils in connective tissue matrices (Hickey et al. 1979). Each knee specimen was evaluated radiologically. Signs of joint pathology were absent.

Because it was impossible to approach all macroscopically distinct fascicles of both cruciate ligaments at the same time with the stylus tip in situ, the ligaments were isolated as preparations containing the ligaments with 2 adjacent bone blocks. These separate preparations allow a near anatomical orientation of each ligament in which as many fibres were tightened as possible. In this way, impression of the tissue with the stylus was prevented during digitisation. To obtain a clear view of all ligament fascicles, obstructing bone parts and synovium were removed from the preparations. They were then oriented as described above and fixed at their bony ends with the aid of acrylic cement (PMMA) in a perspex support, to which the source was also rigidly fixed (Fig. 1).

All measurements were performed in 3 steps. First, the outlines of the whole ligament insertion sites were measured. Next, the courses of the superficial fascicles were measured from the femoral to the tibial insertion sites, analogous to the assessment used by Butler (1989). Fibre bundles were then identified as sets of fascicles with the same directions and about the same cross-sectional areas halfway to their insertion sites. While being very careful to follow the fibre orientations during dissection, each bundle identified was separated artificially with a blunt dissector from the rest of the ligament. Subsequently, the contour lines of both insertion sites were measured with the Isotrak

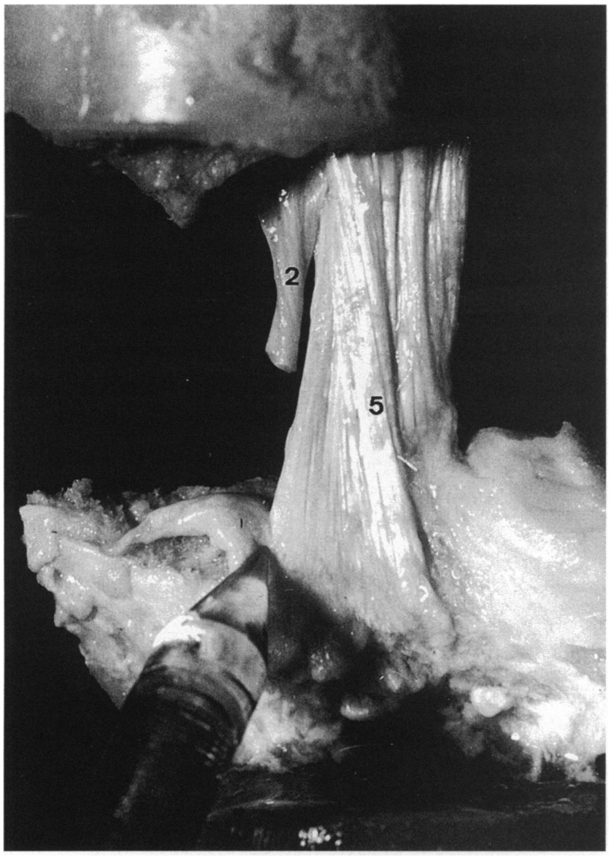

Fig. 2. Posterior view of PCL 3 during the measurement of the tibial insertion site of fibre bundle 2. Fibre bundle 1 has already been dissected. Note the oblique course of bundle 5.

system (Fig. 2). After the preparation of the superficial bundles from the femur and the tibia, the courses of the internal fascicles and insertion sites of the internal bundles of the ligaments were also recorded.

To obtain functional representations of the major fascicle orientations in the ligaments, the geometric centres of the bundle insertion sites were calculated based on the recorded data. Corresponding centres of insertion sites were connected by straight lines. For the ACLs, 9 lines were defined for knee specimens 1 and 2, and 8 for knee specimen 3. For the PCLs, 6, 7 and 10 lines were defined. The lines were numbered according to the sequence of bundle preparation.

To serve as a data base for future functional studies, it is necessary to transfer all bundle insertion sites to a recognisable anatomical position of the knee joint for which the extended position was chosen. Therefore, a relationship is needed between the bone–ligament–bone preparation mounted at the support and the bone–ligament–bone preparation in the in situ situation. The relationship is represented by the 3-dimensional coordinates of at least 3 markers in both bones in both positions. To measure these coordinates, a technique termed Röntgen Stereophotogrammetric Analysis was applied (Selvik, 1974; de Lange et al. 1985). The markers used were radio-opaque pellets fixed near the insertion sites of both cruciate ligaments. X-ray stereograms were made of these markers in the extended knee joint as well as in the bone–ligament–bone preparations mounted in the support and their 3-dimensional positions reconstructed. Knowing the relationship between the different orientations of the ligament insertion sites, it was possible to displace the bone–ligament–bone preparations in the in situ orientation afterwards.

RESULTS

Anatomical description of fibre courses

In a lateral view, the fibres of the ACLs fan out towards the femoral and tibial insertion sites: the ligaments are narrower at their midpoints and wider near their insertion sites (Fig. 3*a*). This fanning was noted for all specimens, although it was more evident for specimen 1 than for the other two. In a posterior view, the tibial insertion sites were broader than the femoral insertion sites, in particular for specimen 1 (Fig. 4*a*). A cleft was discernible at the posterior aspects of all 3 ligaments, indicating the posterior border between the anteromedial bundle and the posterolateral bundle, as was described by Girgis et al. (1975). The anterior border between these 2 bundles was less clear.

Both the lengths and the widths of the PCLs were larger than those of the ACLs. No marked differences in fibre orientations were found between the 3 PCLs (Figs 5*a*, 6*a*). A slight outward fanning of the fibres was visible in the posterior view towards the femoral and tibial insertion sites. Most prominent in all 3 PCLs was the so-called 'reinforcing' bundle (Van Dijk, 1983). Its course over the posterior surface of the PCL from medial at the femur to lateral at the tibia gave the PCL an endorotated appearance (Fig. 6*a*). The fibres lateral from this reinforcing bundle also had an oblique course, although to a lesser extent. The lateral fibres were connected to the proximal–anterior side of the lateral part of the tibial insertion site. This was clearly seen in a medial view of the PCL of knee specimen 1 (Fig. 5*a*).

Connectivity maps

The ways in which the femur and tibia were connected by bundles, the connectivity maps, were consistent for

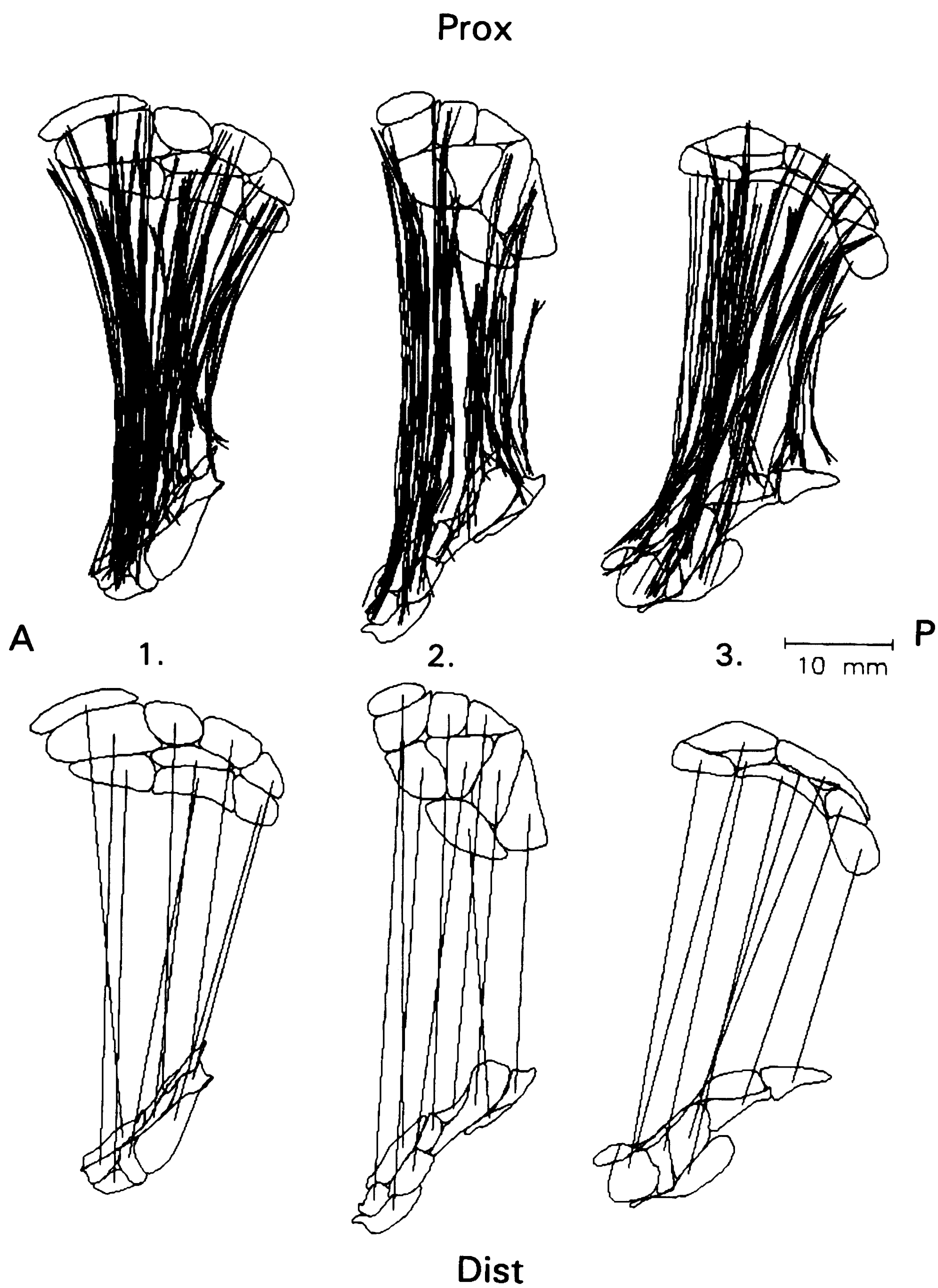

Fig. 3. Medial view of (upper panels) the anatomical courses of the fibres as well as of (lower panels) the straight-line representations of the anterior cruciate ligaments of specimens 1, 2 and 3 fixed in the perspex support. The orientations (P, posterior; A, anterior; Prox, proximal; Dist, distal) correspond approximately with the anatomical orientations.

the 3 ACLs in the sense that the anterior part of the femoral insertion site was connected to the anterior part of the tibial insertion site, the posterior part to the posterior part, the proximal part to the medial part and the distal part to the lateral part (Fig. 7). In their courses, fibre bundles which were neighbours at some point did not always remain neighbours. For knee specimens 1 and 2, it was noted that the centrally inserted fibre bundles at the femur, 6 and 8 respectively, and the most anteriorly inserted fibre bundles at the femur, 4 and 3 respectively, were not neighbours at the femur, while they were at the tibia. The convergence of these fibre bundles at the tibia resulted in a divergence of fibre bundles 3 and 5 of knee specimen 1, and of fibre bundles 5 and 6 of specimen 2. The fibre bundles in the posterolateral corner of the ACLs remained neighbours. A comparable connectivity pattern of fibre bundles was visible for specimen 3, although this was less clear. Clear differences between the overall contour lines of the insertion site areas were visible between the 3 ACLs, in particular for the tibial insertion sites. The

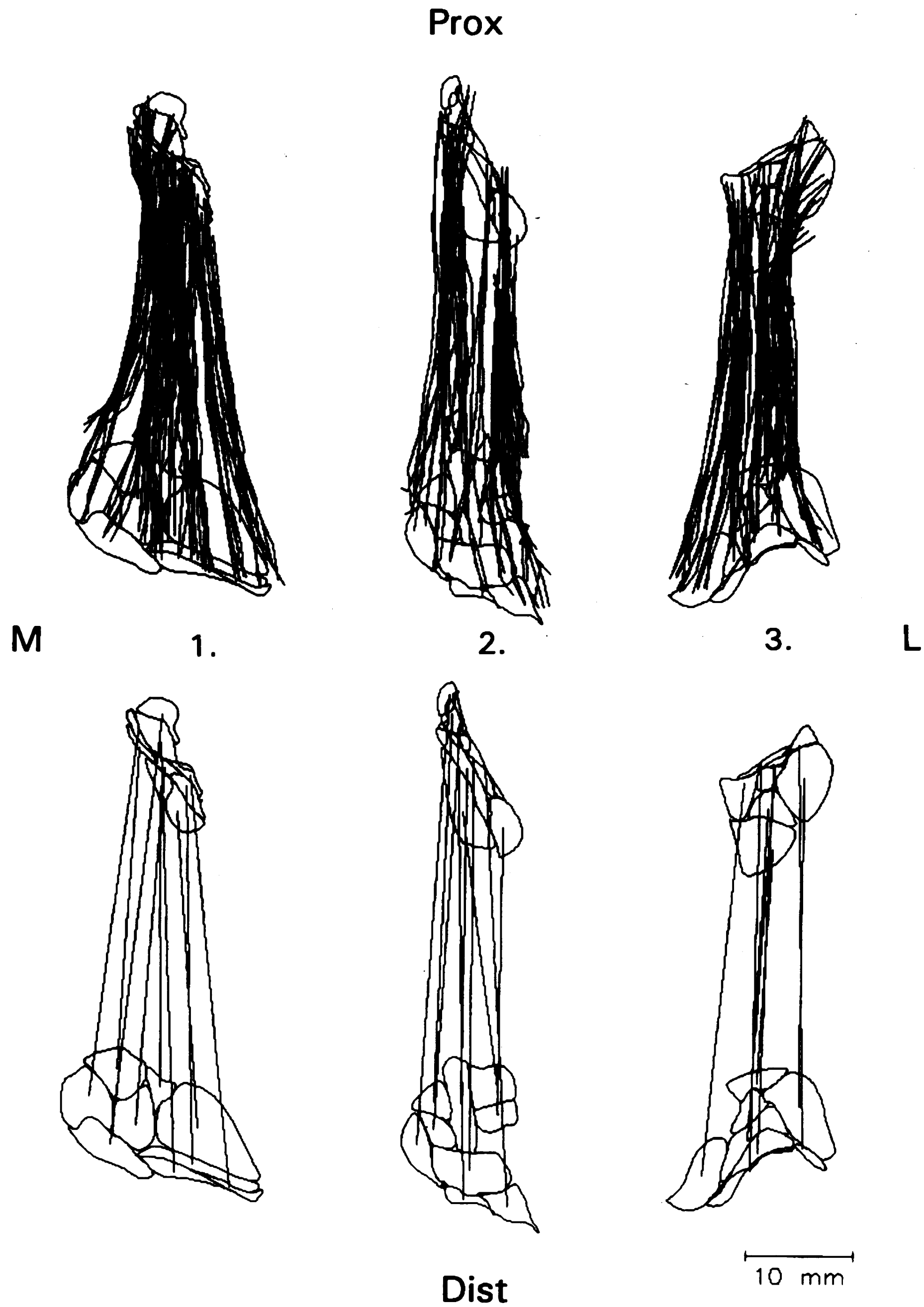

Fig. 4. Posterior view of (upper panels) the anatomical courses of the fibres as well as of (lower panels) the straight-line representations of the anterior cruciate ligaments of specimens 1, 2 and 3 fixed in the perspex support. The orientations (M, medial; L, lateral; Prox, proximal; Dist, distal) correspond approximately with the anatomical orientations.

tibial insertion site of specimen 1 was oval-shaped, with the long axis in the medial–lateral direction. The insertion site area of specimens 2 and 3 was approximately horseshoe-shaped. The shapes of the femoral insertion sites were semicircular, with the straight edge at the anterodistal side.

The connectivity maps of the 3 PCLs were comparable with each other (Fig. 8); the anteriorly inserted fibres at the femur were connected to the proximal–anterior part of the tibia and the posteriorly inserted fibres to the distal–posterior part of the tibia. Note that the fibre bundles which were inserted laterally at the femur shifted anteriorly, due to the obliquely inserting fibres of the reinforcing bundle in the posterolateral corner. Because of its oblique course, it was clear that the reinforcing bundle did not remain a neighbour of the other bundles of the PCL. Just as for the ACLs, the contour lines of the overall insertion sites of the PCLs varied. The femoral insertion sites were approximately oval-shaped, with a

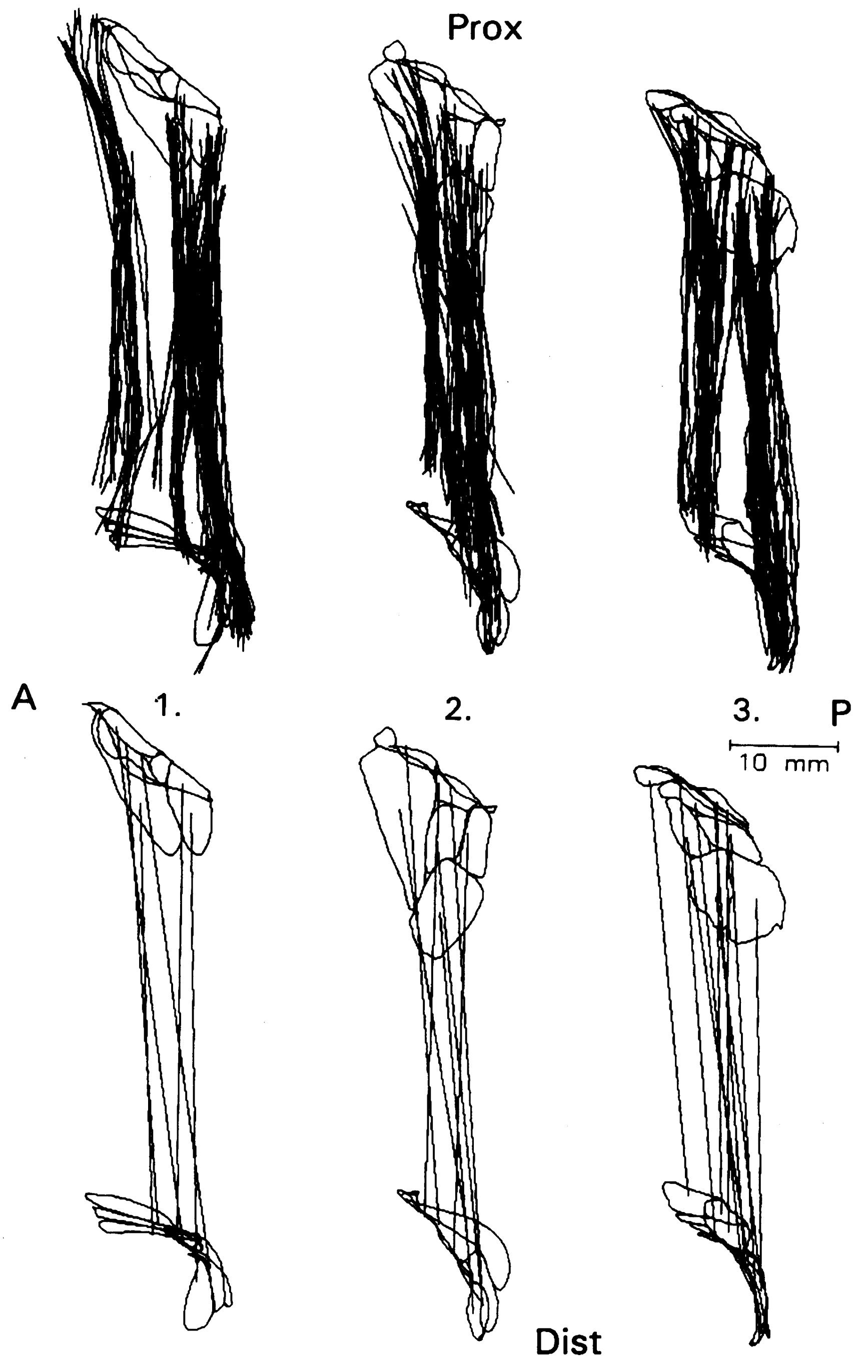

Fig. 5. Medial view of (upper panels) the anatomical courses of the fibres as well as of (lower panels) the straight-line representations of the posterior cruciate ligaments of specimens 1, 2 and 3 fixed in the perspex support. The orientations (P, posterior; A, anterior; Prox, proximal; Dist, distal) correspond approximately with the anatomical orientations.

variable ratio of the medial–lateral to the anterior–posterior axis. The tibial insertion sites were more or less rectangular.

Straight-line representations of cruciate ligaments

The fibre bundles have been represented by straight lines (lower panels of Figs 3–6). Although the straight-line representations lack the fanning of the ligaments toward their insertion sites, the main fibre-directions are well represented. After transformation of the straight-line representations to their anatomical positions in the extended knee joint it can be seen that, in contrast to the lines in the bone–ligament–bone preparations, the ACL descends anteriorly and medially, in particular at the posterolateral side (Fig. 9). The PCL descends posteriorly, in particular the

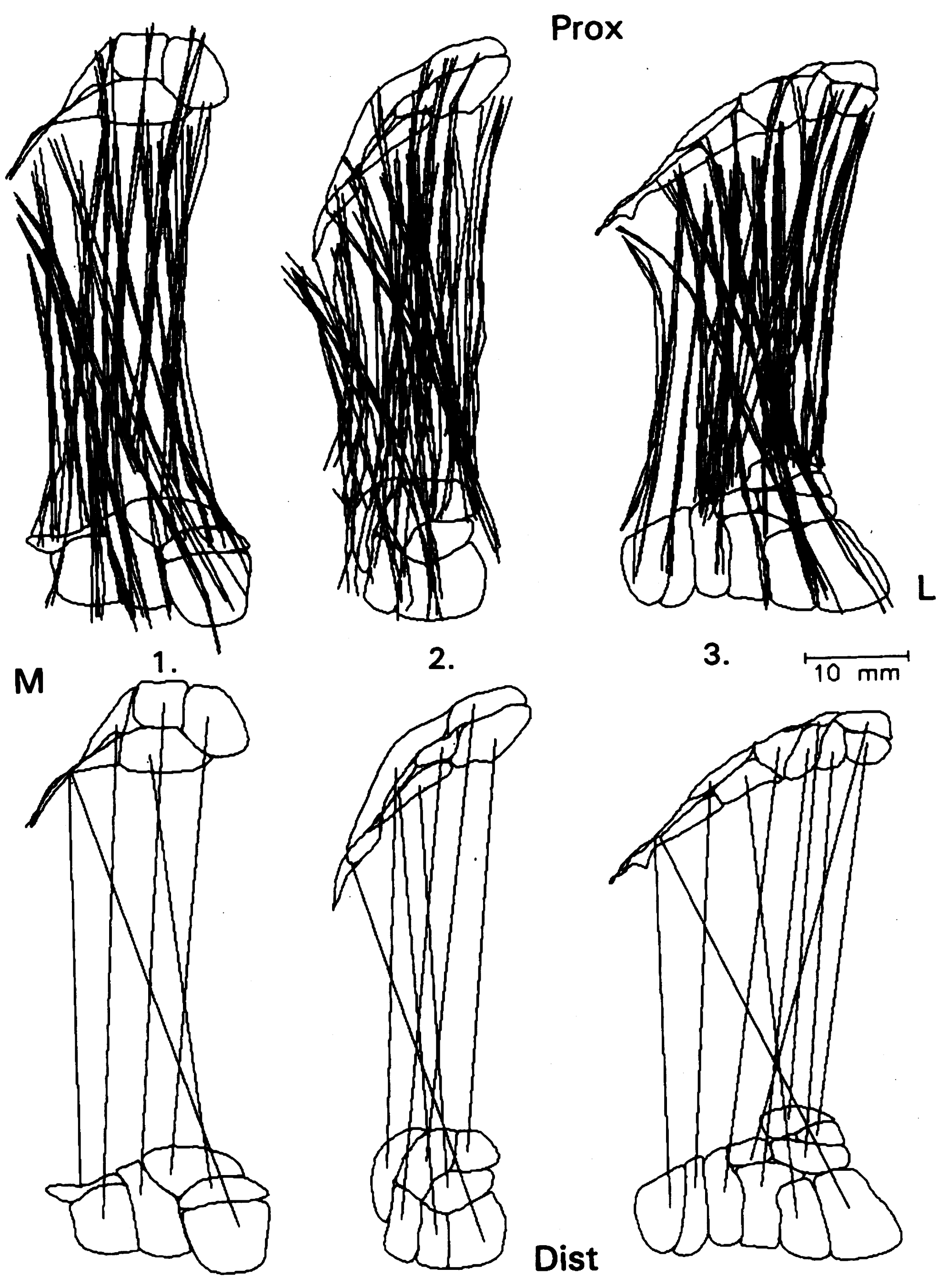

Fig. 6. Posterior view of (upper panels) the anatomical courses of the fibres as well as of (lower panels) the straight-line representations of the posterior cruciate ligaments of specimens 1, 2 and 3 fixed in the perspex support. The orientations (M, medial; L, lateral; Prox, proximal; Dist, distal) correspond approximately with the anatomical orientations.

anterior fibre bundles (Fig. 10), and laterally, in particular the reinforcing bundle.

DISCUSSION

In the present study, the cruciate ligaments were represented by 6–10 fibre bundles. This is more detailed than previously presented. The representations are realistic in the sense that they are based on the orientations of the fascicles of which the ligaments are composed. Hence, the main directions of the ligament fascicles are preserved.

The subdivision of the ligaments into fibre bundles is not based on possible layers of fibrous tissue surrounding these bundles. For this reason, the identification of the bundles resulted in nonidentical subdivisions for the 3 different ACLs, as well as for the 3 PCLs. The failure to discern anatomically distinct bundles in the cruciate ligaments is in accord with Odensten & Gillquist (1985), Fuss (1989), Welsh

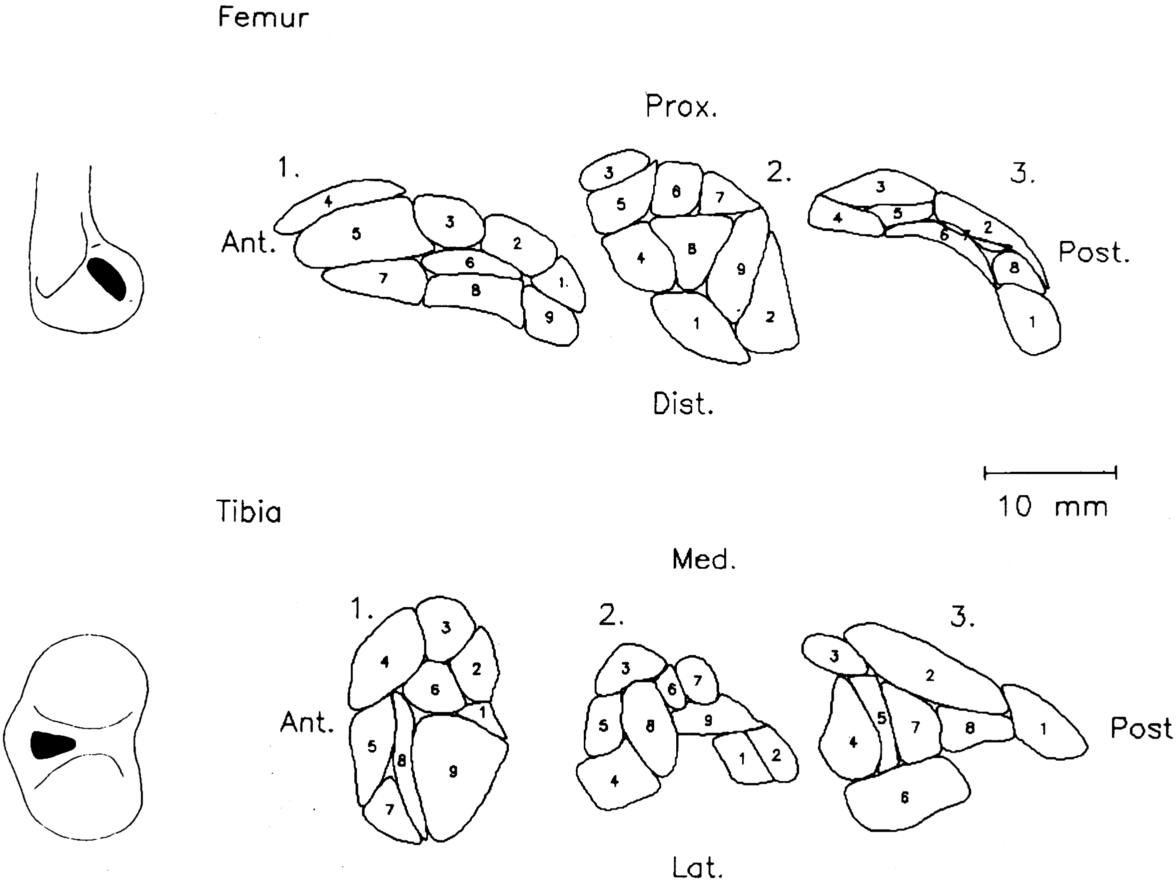

Fig. 7. The femoral and tibial insertion sites of the bundles defined in the ACLs of specimens 1, 2 and 3. The insertion sites are numbered according to the sequence of bundle preparation. The orientations (Ant, anterior; Post, posterior; Med, medial; Lat, lateral; Prox, proximal; Dist, distal) correspond approximately with the anatomical orientations. Note that in particular at the anteromedial side of the ligaments, the fibre bundles do not remain neighbours.

(1980) and Dorlot et al. (1983), but not with authors who described 2 or 3 anatomically distinct bundles (Girgis et al. 1975; Norwood & Cross, 1979; Dawkins & Amis, 1985).

Although the number of fibre bundles varied between the ligaments, the way in which the tibial insertion site was connected to the femoral insertion site was consistent for the different ACLs as well as for the different PCLs. This indicates common distributions of fascicle direction in the cruciate ligaments. In this case, it is possible to predict where fibres originating at the tibia should attach at the femur. This allows the use of the connectivity maps of one ligament for other ligaments as well, as was performed by Fuss (1991). In general, Fuss (1989) found similar connectivity maps as in the present study, in the sense that the bundles originating most anteriorly inserted most anteriorly at the femur and those originating most posteriorly inserted most posteriorly. However, no mention was made by Fuss (1989) of two phenomena clearly seen in the present study, namely the changing interrelationship of the fibre bundles from the femoral to the tibial insertion site and the differences in the shapes of the insertion sites.

For functional analyses of the cruciate ligaments, length patterns are usually derived from the changing positions of the insertion site of the fibre bundles in the knee-joint (van Dijk et al. 1983). It is therefore necessary to know how the straight-line representations are oriented in the various anatomical positions of the knee-joint. Röntgen Stereophotogrammetric Analysis allows this transformation. Because of the high precision of this analysis (Blankevoort et al. 1988; de Lange et al. 1990), the geometry measurements can be transferred to the anatomical situation with hardly any loss of precision. The advantage is that the measurements of the bundle insertion sites can be performed in a more comfortable situation than the in situ situation. Ligament inaccessibility is avoided.

The anatomy-based connectivity maps obtained are important for two main purposes. First, they provide insertion points of the cruciate ligaments necessary for functional analyses of these structures. In this way,

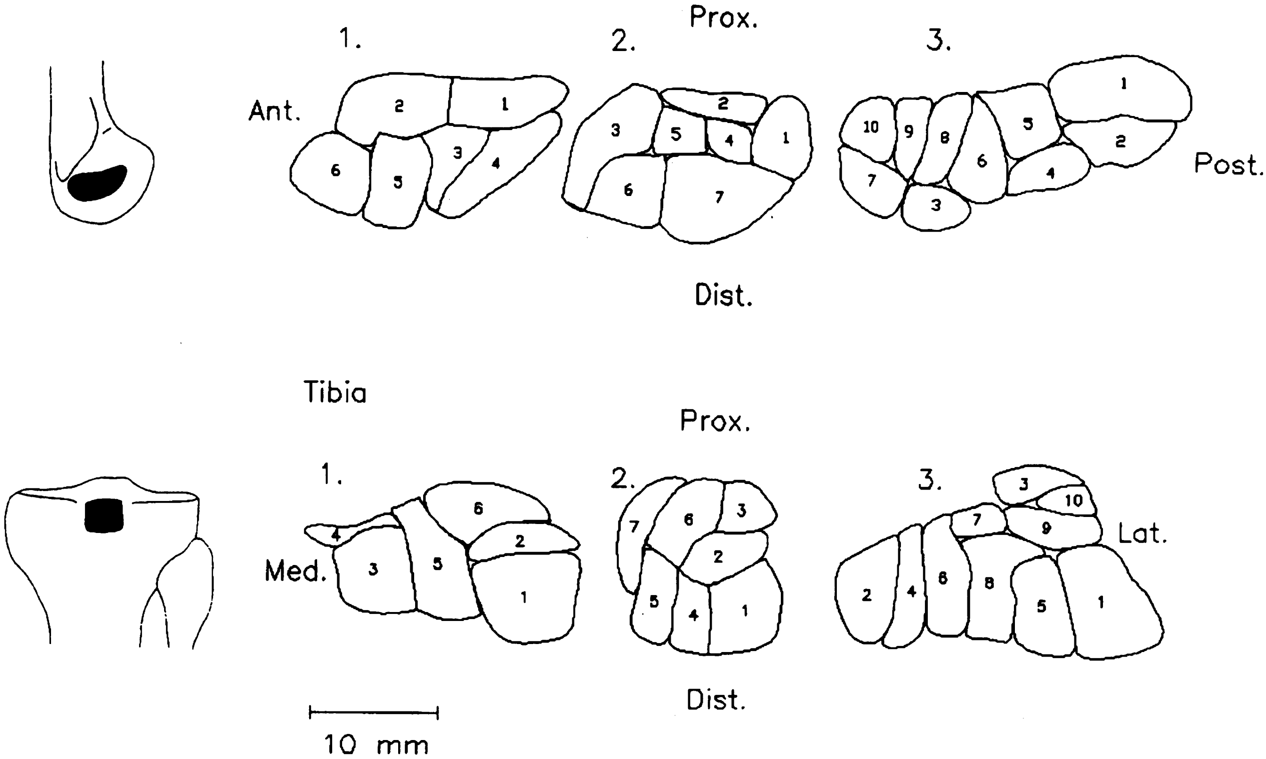

Fig. 8. The femoral and tibial insertion sites of the bundles defined in the PCLs of specimens 1, 2 and 3. The insertion sites are numbered according to the sequence of bundle preparation. The reinforcing bundles are numbered 1 and 2 (spec. 1), 1, 2 and 4 (spec. 2) and 1 and 5 (spec. 3). Note that the reinforcing bundles do not remain neighbours with the other fibre bundles of the PCLs in their course from the tibia to the femur. The orientations (Ant, anterior; Post, posterior; Med, medial; Lat, lateral; Prox, proximal; Dist, distal) correspond approximately with the anatomical orientations.

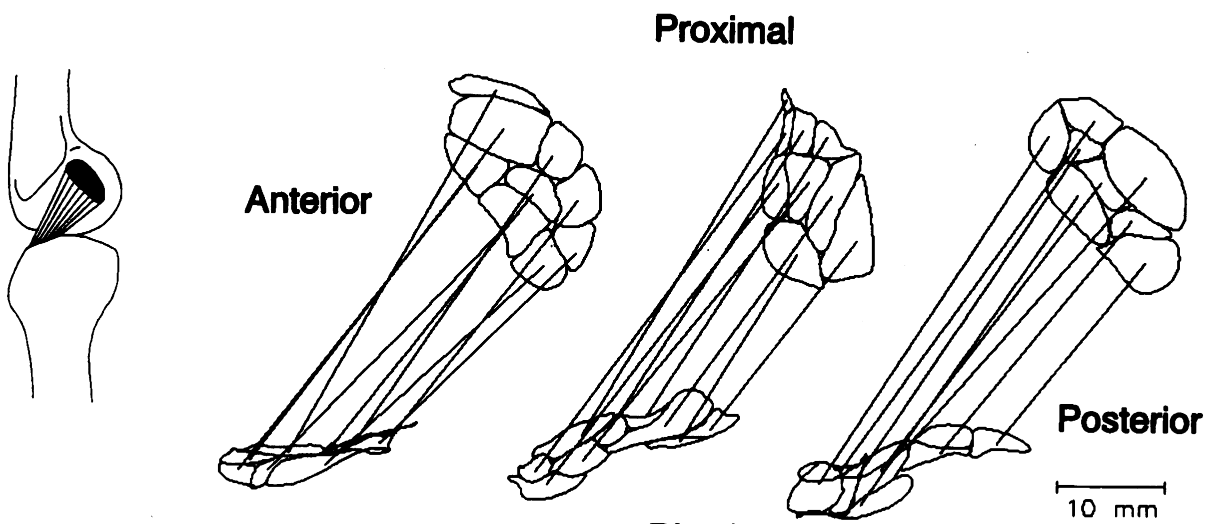

Fig. 9. Medial view of the straight-line representations of the ACLs after transformation to the extended knee joint.

line representations of these knee ligaments can be constructed in mathematical knee-joint models with which these functional analyses can be performed (Hefzy & Grood, 1988; Essinger et al. 1989; Blankevoort, 1991; Huiskes, 1992; Hirokawa, 1993). There is some evidence that these straight-line representations are valid for functional analyses of the mechanical behaviour of knee ligaments, in the sense that whole joint models behave similarly to experimental knee-joint specimens (Essinger et al. 1989; Blankevoort, 1991; Mommersteeg et al. 1995). Secondly, the information about the organisation of the

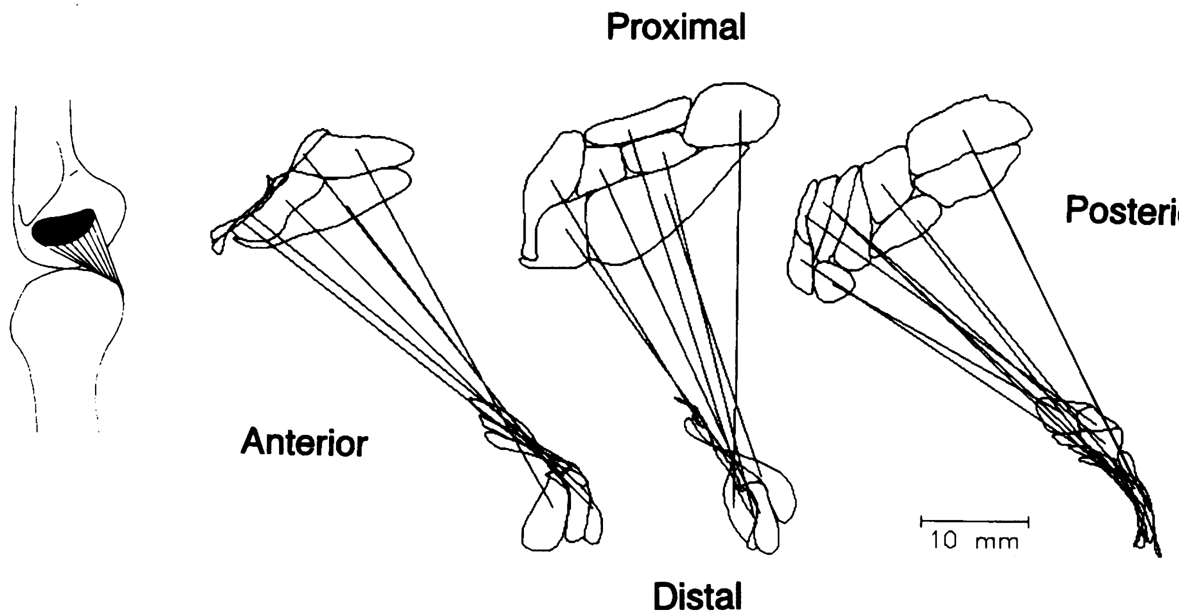

Fig. 10. Medial view of the straight-line representations of the PCLs after transformation to the extended knee joint.

fibre bundles is useful for constructing a structural analogy in the design of cruciate ligament prostheses, while the knowledge about the insertion sites of the bundles is critical for the proper positioning of these prostheses.

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