Meniscal movement
AN IN-VIVO STUDY USING DYNAMIC MRI
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We present the first study in vivo of meniscal movement in normal knees under load. Using an open MR scanner, allowing imaging in physiological positions in near to real-time, 16 young footballers were scanned moving from full extension to 90° flexion in the sagittal and coronal planes. Excursion of the meniscal horns, radial displacement and meniscal height were measured.

On weight-bearing, the anterior horn of the medial meniscus moves through a mean of 7.1 mm and the posterior horn through 3.9 mm, with 3.6 mm of mediolateral radial displacement. The height of the anterior horn increases by 2.6 mm and that of the posterior horn by 2.0 mm. The anterior horn of the lateral meniscus moves 9.5 mm and the posterior horn 5.6 mm, with 3.7 mm of radial displacement. The height of the anterior horn increases by 4.0 mm, and that of the posterior horn by 2.4 mm. In non-weight-bearing, the anterior horn of the medial meniscus moves 5.4 mm and the posterior horn 3.8 mm, with 3.3 mm of radial displacement. The anterior horn of the lateral meniscus moves 6.3 mm, and the posterior horn 4.0 mm, with 3.4 mm of radial displacement. The most significant differences between weight-bearing and non-weight-bearing were the movement and vertical height of the anterior horn of the lateral meniscus.

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Subjects and Methods
We recruited 16 normal male volunteers aged 15 to 18 years from a group of footballers with no known abnormality of the knee. A 0.5 Tesla superconducting open magnet MR scanner (Signa SPio; General Electric Medical Systems Milwaukee, Wisconsin) was used to generate the images. The vertically orientated ‘double-doughnut’ design allows the patient to be positioned both sitting and standing in the 56 cm gap between the two rings. A specially constructed support frame was used against which the

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subject could stand and allow the knee to be scanned through an arc of flexion-extension while weight-bearing (Fig. 1). A second support frame with a hinge positioned behind the knee was used to allow the subject to sit in the scanning area, with movement from flexion to extension produced passively when relaxed and bearing no load. The knee was supported in the frame to control and prevent movement artefacts.

Each volunteer was scanned with one knee in both erect and weight-bearing positions, and when sitting, relaxed bearing no weight. Images were taken in near real time using a fast inversion (TE, TR, T1, flip) recovery prepared sequence at increments of 10° from 0° to 90° of flexion. Initially, with the knee extended, images of sagittal sections, 6 mm in thickness, were taken of the mid-medial and mid-lateral compartments to identify the planes producing maximal meniscal size. These planes were then maintained as the knee was moved using the ‘flashpoint tracking system’ (Image Guided Technologies, Boulder, Colorado) consisting of a device applied around the leg just below the knee which has light-emitting diodes mounted on it (Fig. 1). Three high-resolution infrared-sensitive cameras located in the roof of the imaging volume detect the diode emissions using a triangulation process. This ensures that the plane of scanning through the knee is constant, despite changes in limb orientation within the imaging volume. Also, coronal images were obtained from a point posterior to the tibial tuberosity in the mid-anterior compartment at maximal meniscal thickness, again using the flashpoint tracking system to maintain this position.

The images were analysed using a General Electric Medical Systems independent console and archived on a laser optical disk for analysis. Movements of both menisci were observed in the sagittal plane in the line of their greatest diameter. The perpendicular distance from the outer inferior edge of the meniscus to the outermost edge of the articular cartilage of the tibial plateau was measured for both the anterior and posterior horns (Fig. 2a). The heights of the anterior and posterior horns were also measured (Fig. 2b). On the coronal sections the distance from the outer inferior edge of the meniscus to the edge of the tibial plateau determined the extent of radial displacement (Fig. 2c). The maximum movement of the meniscus through the flexion-extension arc was calculated from the measurements taken. These figures were used to obtain mean values and standard deviations for the excursion of the anterior and posterior horns of each meniscus, for the change in height of the meniscal horns and for radial displacement of each meniscus.

Results

The MR images were archived for all 16 knees scanned. At the time of analysis only 14 of these sets of images
were deemed suitable for measurement of meniscal movement. Two studies were degraded by artefacts due to movement by the subjects. No abnormal pathology was identified in the soft tissues, bone, ligaments or menisci of any of the knees scanned. The distances moved by each part of each meniscus are given in Tables I and II.

Schematic representations are given in Figure 3. Figures 4 and 5 are scans taken in progressive degrees of flexion. Meniscal movement through the arc of flexion is clearly evident in both the sagittal and coronal planes.

The ten sets of movements in the paired groups, erect-weight-bearing versus sitting-non-weight-bearing, were analysed using paired Student’s t-tests. Our findings showed strong evidence to suggest that the movement of the anterior horn of the lateral meniscus was greater when the knee was weight-bearing (p = 0.005). There also appeared to be a difference in the change in height of the anterior horn of the lateral meniscus between weight-bearing and non-weight-bearing (p = 0.036). Otherwise, there was no statistically significant difference between meniscal movements in the erect and sitting groups. The Student’s t-test assumes that the differences between the two measure-

![Fig. 3a](image1) ![Fig. 3b](image2)

Diagrams showing the mean movement (mm) in each meniscus during flexion a) erect and weight-bearing and b) sitting, relaxed, bearing no weight. These are not to scale.

![Fig. 4a](image3) ![Fig. 4b](image4) ![Fig. 4c](image5)

MR image in the sagittal plane of a knee a) in extension b) in 40° of flexion and c) in 75° of flexion. The arrows show the position of the anterior and posterior horns of the lateral meniscus.
ments are normally distributed. In order to confirm this the Shapiro-Francia test for normality was applied which showed a normal distribution. Non-parametric signed-rank tests showed similar findings.

The menisci remained in constant contact with both the tibial and femoral articular surfaces throughout the arc of flexion, confirming the findings of the cadaver study of Thompson et al. It was noted, however, that in several of the knees the anterior horn of both menisci overhung the tibial plateau in extension and early flexion. We also examined the change in meniscal height as an additional parameter of meniscal deformation and observed an increase in vertical height with flexion.

Discussion

The menisci are thought to carry between 40% and 70% of the load across the knee, thus protecting the articular surface from compressive stress. In order to do this, they must resist extrusion from the joint space as load is applied. This action is dependent on the longitudinal orientation of intrameniscal fibres, the attachments of the anterior and posterior horns and intermeniscal connections producing a circular construct, resulting in the generation of circumferential tension in the meniscus as vertical load is applied: the hoop-stress theory. Movement of the meniscus during knee flexion ensures maximal congruency with the articulating surfaces while avoiding injury to it. Dynamic congruity facilitates load transmission, stability, and lubrication. The design of the open MR scanner has made possible our study of meniscal movement in the normal knee under weight-bearing conditions through a range of flexion.

Most previous studies of meniscal movement have been hindered by disruption of the normal anatomy performed in order to allow direct visualisation. Poor imaging techniques were used and studies were often performed on cadaver knees. Our results confirm the observation of Thompson et al, who studied five fresh cadaver knees bearing no weight. The lateral meniscus does move more than the medial and the anterior horns more than the posterior. The posterior horn of the medial meniscus moves least. These findings are in keeping with tibiofemoral kinematics and patterns of meniscal pathology. The anterior horns must move in order to maintain congruency of the joint surface while the cam-shaped femoral condyles move on the tibia during flexion. The soft-tissue attachments of the menisci are most substantial at the posterior horns, especially the medial, and therefore movement is restricted here. This has the effect of providing stability, preventing anterior tibial translation when the posterior horns of the menisci, with their wedge-shaped cross-section, impact like ‘wheel-blocks’ against the posterior femoral condyles. Mobility would undermine this function. The relative immobility of the posterior part of the medial meniscus may account for the frequency with which this part is torn. Being fixed, it may be loaded more than other parts of the meniscus making it vulnerable. Thompson et al did not observe meniscal movement under conditions of load. Our own movements under load revealed statistically significant differences in movement, only for the anterior horn of the lateral meniscus. It could be that the number of knees in our study (14) was too small for the increases in movement on weight-bearing observed for other parts of the menisci (the posterior horns of the lateral and both horns of the medial) to reach statistical significance.

Thompson et al did not evaluate ‘mediolateral’ meniscal movement in the coronal plane, but suggested that a significant amount of this would occur during knee flexion. We have shown that, compared with the anterior and posterior horns, relatively little movement takes place.
menisci would not be effective in increasing the surface area of the femoral articulation if they moved out of the tibiofemoral articulation under load or with knee flexion. Load between the femur and tibia generates a compressive force on the meniscus which, with its wedge-shaped cross-section, results in an outwardly directed radial vector. This tensions the longitudinal fibres in the meniscus which is fixed at its anterior and posterior horns. This 'hoop-stress' concept explains how the menisci stay between the tibial and femoral joint surfaces while allowing them to move at their posterior and especially anterior poles, maximising joint congruency. Extensive peripheral meniscal attachment would oppose the tendency to extrusion, but would also prevent this necessary meniscal movement. If significant radial displacement occurs then joint congruency will be decreased, resulting in an increase in contact stresses on the articular cartilage. This follows disruption of normal meniscal ultrastructure by tears or damage to the anterior or posterior meniscal attachments and, hence, their association with degeneration of the joint surface.

Kenny reported radial displacement in the coronal plane of medial menisci viewed on MRI in knees, with and without Fairbank's radiological signs (an antero-posterior ridge projecting downwards from the medial femoral condyle, generalised flattening of the marginal half of the femoral articular surface and narrowing of the joint space after meniscectomy). None of the knees in the study by Kenny had had meniscectomy. His finding was that the greatest radial displacement of medial menisci was seen in those knees with evidence of Fairbank's radiological signs. This stimulates debate as to whether an abnormally mobile medial meniscus leads to joint degeneration or whether, as seems more plausible, damage to the articular surface leads to failure of the meniscus. Our study demonstrates radial displacement of both menisci in the normal knee and provides a useful baseline for this parameter.

An unexpected finding of our study was the increase in vertical height of the peripheral margin of the meniscus. This presumably reflects tension on the meniscus by its peripheral attachment in the course of movement. A potentially important meniscal attachment is the anterior intermeniscal or transverse genual ligament. This ligament is partially important meniscal attachment is the anterior inter-

References