3D Meniscal Kinematics and Deformation with Knee Flexion and Loading: A Novel In-Vivo MRI Study of the Knee

Daniel Watling, BEng¹, David Williams, BEng¹², Gemma M. Whatling, MEng PhD¹, Cathy A. Holt, BEng PhD¹.
¹Cardiff University, Cardiff, United Kingdom, ²Arthritis Research UK Biomechanics and Bioengineering Centre, Cardiff, United Kingdom.


Introduction: The meniscus has been shown throughout the literature to be functionally important in the knee, providing load transmission, shock absorption, proprioception, joint stability and aid joint lubrication [1]. Meniscal tears are a recognised risk factor for knee osteoarthritis, often occurring during twisting or squatting. In-vivo understanding of meniscus biomechanics is limited to evaluating single 2D Magnetic Resonance Imaging (MRI) slices, low resolution imaging or does not consider joint loading [2]. The purpose of this study is to develop novel, high resolution, 3D MR imaging and analysis techniques to quantify 3D, patient specific, in-vivo menisco-tibial kinematics and meniscus deformation behaviour during knee rotations and loading.

Methods: MRI was performed on 5 healthy knees with a Signa HD-xt 3.0T scanner (GE Medical Systems, USA.) using a Fast Imaging Employing Steady State Acquisition (FIESTA-C) sequence. The FIESTA-C sequence provides 3D, high resolution, high contrast and low noise images in very short scan times (1.6 mm slice thickness, 6 minute acquisition time). A custom MR compatible knee loading device was used to apply approximately 200N of load along the lower limb. The knee was positioned in extension and 50 degrees flexion under load and 0, 25, 50 and 130 degrees of passive flexion. 3D meniscus and tibia models were created by segmenting MR scan data (Simpleware Ltd.). Meniscal motion is described by the co-ordinate position of the meniscus centroid relative to a tibial local coordinate system (LCS). This is defined by identifying anatomical landmarks on 3D bone models reconstructed from additional 3D MR imaging of the ankle [3]. Analysis of meniscus 3D volume-depth distribution is achieved by examining the volume distribution of the meniscus throughout its height (z tibial LCS direction). The tibia bone model is incrementally translated superiorly forming a meniscus cutting plane. A Boolean subtraction of the menisci-tibia overlap is performed at each increment and the new volume of the meniscus is calculated (Figure 1).

Results: Figure 2 shows the approach to defining changes in meniscus shape in response to altered loading. Small changes in measured meniscal shape, thought to be representative of compressions, were observed in the early stages of passive flexion. As the angle of passive knee flexion increased from 25° to 50°, a large increase of both the medial and lateral meniscus response to loading in terms of shape was observed. Axial load in extension and axial load in flexion did not introduce additional shape change response of the menisci compared to that found during passive flexion. Example results show passive knee flexion up to 140 degrees in Figure 3. In contrast to the majority of published findings, the medial and lateral menisci appear equally mobile at the extreme range of passive knee flexion. Loading introduces additional posterior motion of both menisci, up to 4.6mm (medial) and
5.2mm (lateral) in the flexed knee. Large variability (SD) observed between subjects was found to be greater than that observed during repeatability studies.

**Discussion:** This study demonstrates the feasibility of imaging the knee under load from which 3D in-vivo meniscus biomechanics can be quantified with high repeatability as the standard deviation of the location of the centroid calculations was within the size of a MRI voxel, <0.6mm. Flexion of the knee appears to introduce compression in the menisci due to ACL tension, while loading appears to introduce greatest posterior translation of both menisci relative to the tibia.

**Significance:** The authors are not aware of any literature quantifying the 3D deformation behaviour in response to loading of the medial and lateral menisci with passive flexion and in the flexed loaded knee, in-vivo and in humans.
Fig. 3: Plan view of tibial plateau in blue, showing the effect of meniscus kinematics in red with 30 degrees (left), 50 degrees (middle) and 140 degrees (right) passive knee flexion relative to the neutral knee in black; white arrows represent the movement of the calculated centroid of the meniscus.