Importance of Patella, Quadriceps Forces and Depth-Wise Cartilage Structure on Knee Joint Motion and Cartilage Response During Patient-Specific Gait Cycle

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Introduction: Use of computational models has become popular in the analysis of knee joint function. Despite being vital to the function of knee, the human patella is commonly omitted from the computational models of knee joints, or the patellar articular cartilage has been implemented as a linear elastic material [1,2]. Furthermore, in previous studies of strains and fluid pressures in patellar cartilage, the implemented gait cycle has been derived from literature and therefore does not represent the subject-specific walking pattern. In this study, we implement depth-wise fibril-reinforced biphasic properties for all cartilage tissues in a knee joint (including patella), and investigate strains and fluid pressures in patellar cartilage during a subject-specific gait cycle determined in a motion laboratory. The study aims to investigate the role of patella and quadriceps forces for the knee joint rotations and translations, and the importance of depth-wise properties of cartilage on mechanical responses of patella. This is important when developing realistic models of human knee joints for the analysis of potential risks of osteoarthritis (OA) in the knee joint.

Methods: Motion and multibody analysis: The gait pattern of the subject (healthy 29-year-old male, 82 kg) was recorded using a ten camera Vicon system (Vicon Motion Systems, UK) and a force plate. The extension-flexion rotation, moments and translational forces of the knee were then calculated using Vicon software (Nexus v.1.7) and LifeMOD (LifeModeler, CA, US) virtual human modeling plug-in and general purpose MD Adams simulation software [3]. The internal-external and varus-valgus rotations were calculated using coupled inverse and forward dynamics simulation approach. The moment arms of the quadriceps and patella tendons were determined from MR images around the epicondylar axis of femur, which is also the axis of rotation of the knee [4]. A previously described biomechanical model was then used to quantify forces acting on the quadriceps tendon during gait [5].

Computational analysis: The finite element model was created by imaging the subject’s left knee with a clinical 3.0 T MRI scanner (Philips, Netherlands) (voxel size 0.5x0.5x0.5 mm³). The segmentation of cartilages, menisci, patella and ligament attachments was done in Mimics v.15.01 (Materialise, Belgium). The tissues were then transformed into a solid geometry and imported into Abaqus v.6.12-3 (3DS, France). All cartilages and menisci were meshed with element type C3D8P. Cartilage and meniscus tissues were defined as fibril-reinforced poroviscoelastic (FRPVE) [6-7] with fibrils oriented along the split-lines in cartilages, while the ligaments and tendons were defined using linear elastic springs [8,9]. In order to simulate the stance phase of gait, the extension-flexion rotation, moments and forces obtained from the motion analysis were implemented into the model through the reference point halfway
between the lateral and medial epicondyles of femur (Fig 1a). Since the extension-flexion movement was implemented as rotation, it was identical in all models and the measurements (Fig 1b). In addition, quadriceps forces were implemented into the model through the quadriceps tendon (Fig 1a) so that the direction of the force followed the extension-flexion rotation of the femur (Fig 1a). The input moment amplitudes (internal-external, varus-valgus) were scaled so that the model-derived rotations matched the measured rotations of the femur. The motion of the reference point was compared to a model without patella as well as to the measured rotations and literature [10]. To examine the effects of the depth-wise collagen fibril network orientations in patella, two material models were used: one with arcade-like fibrils (inhomogeneous model) and another one with fibrils parallel to the surface at all depths (homogeneous model).

**Results:** During the entire stance phase of gait, the rotations of the model with patella and tendons (including quadriceps forces) followed closely the experimentally measured rotations and literature data [10] (Figs 1b-d). Without patella in the model, the internal-external rotation (Fig 1c) was substantially increased. On the other hand, patella and quadriceps forces caused only a minimal change in the varus-valgus rotation (Fig 1d) during the second peak force (at 80% of stance). Arcade-like collagen fibril orientation decreased maximum principal strains (Fig 2a, b) and fibril strains (Fig 2c, d) at all depths in the patellar cartilage, especially during the first peak force (at 20% of stance). Fluid pressure was not substantially altered by the depth-wise properties, only a slight increase in the surface and decrease at the cartilage-bone interface was observed (Fig 2e, f).

**Discussion:** The present study investigated the importance of patella on the knee joint motion as well as strains and fluid pressures in the patellar cartilage (with depth-wise fibril-reinforced biphasic properties) during gait. The subject-specific gait pattern was determined in a motion laboratory and used as an input and validation of the model. Inclusion of patella and quadriceps forces substantially reduced the internal-external rotation, increasing the match between the model results and experimentally determined rotations. This suggests that patella and quadriceps are important in moment and force controlled computational knee joint models. They are needed to realistically simulate the effect of knee joint disorders (e.g. due to ligament failure) on cartilage responses. This type of information could be used for treatment planning. The arcade-like fibril network structure decreased especially tensile strains at all depths of the cartilage compared to the homogeneous network. The results suggest the orientation of the fibrils plays a major role in decreasing the maximum strains in patellar cartilage, thus potentially reducing the risk of OA. The results are in accordance with our previous work [11].

**Significance:** For the first time, we developed and validated a computational knee joint model with a highly advanced material model for cartilage (including patella) and patient-specific gait and quadriceps force data. The study emphasizes the importance of patella on knee joint motion and arcade-like collagen architecture on the load-bearing of patellar cartilage. This study takes a step towards developing a method for non-invasive diagnostics of joint disorders and treatment planning through analysis of contact mechanics.
Figure 1. (a) Finite element model. Rotations of the femur (at the reference point): (b) extension-flexion (c) internal-external (d) varus-valgus.
Figure 2. Inhomogeneous vs. homogeneous patellar cartilage. (a)-(b) Maximum principal strains, (c)-(d) fibril strains and (e)-(f) fluid pressures during the first peak force of gait (20% of stance).