The Effect of External Loading on the 3D Patellar Tendon Moment Arm Measured with Dynamic MRI

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INTRODUCTION

Muscle forces are an important determinant of the knee cartilage contact loads that arise during movement. However, models used to estimate muscle forces often rely on a generic description of knee musculoskeletal geometry [1] in which moment arms are assumed invariant with load. Recent dynamic imaging studies have shown that moment arms can vary under functional loading conditions [2]. For example, a recent fluoroscopic study found significant variation in the patellar tendon moment arm with quadriceps contraction [3]. However, the analysis was limited to the sagittal plane and thus could not account for three-dimensional effects [2,4]. The goal of this study was to compare the 3D patellar tendon moment arms between movements that involved active shortening and lengthening quadriceps contractions.

METHODS

High resolution static MR images were used in conjunction with dynamic MR imaging to compute subject-specific patellar tendon moment arms about the knee finite helical axis. Eight healthy subjects (four male, four female, ages 22-28 years) participated. Each subject performed cyclic knee flexion-extension (30 cycles per minute) through ~35 degrees of motion within the bore of a MR scanner (Fig. 1a). A MRI compatible loading device was used to apply either elastic or inertial loads about the knee [5], which induced quadriceps activity with knee extension or flexion, respectively (Fig. 1c). Subjects performed three trials for each loading condition.

CINE phase contrast imaging [6] was used to measure 3D tissue velocities within a sagittal-oblique imaging plane (pixel size of 0.94 x 0.94 mm) that bisected the femur, tibia, and patella (Fig. 1b). At each frame of the cyclic movement, linear least squares was used to calculate the translational and angular velocity of the femur, tibia, and patella that best agreed with measured pixel velocities. Forward-backward and Fourier integration of the rigid body velocity data was then performed to compute the 3D translations and rotations of the tibio-femoral and patella-femoral joints [7].

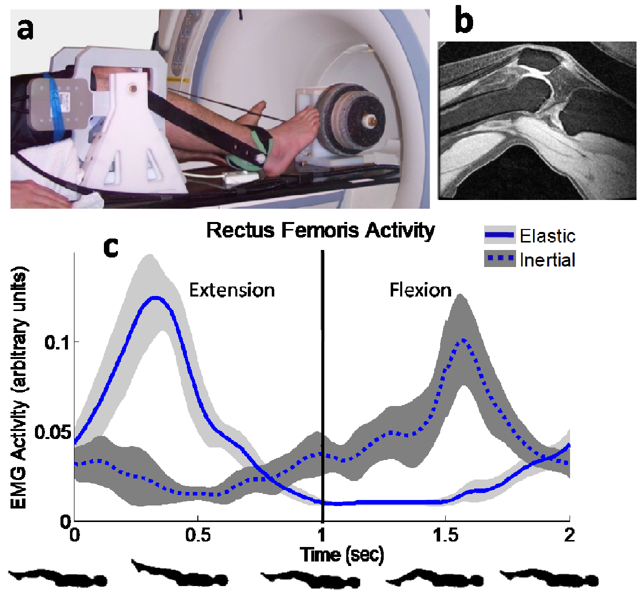

Figure 1: (a) MR compatible loading device, (b) Sagittal-oblique imaging plane, (c) Quadriceps activity (shown for one representative subject) was induced during either knee extension (elastic loading) or flexion (inertial).

The static MR images were segmented to create subject-specific knee models in which the origin and insertion of the patellar tendon could be identified. Anatomical landmarks were then co-registered between the dynamic and static image data [8]. Tibiofemoral kinematics were used to compute the instantaneous finite helical axis (FHA) of the tibia with respect to the femur at each frame (Fig. 2) [2,8]. The patellar tendon moment arm was then determined as the shortest distance between the patellar tendon line of action and the joint axis [2]. We did not compute moment arms near the ends of the knee range of motion since small joint velocities at these phases introduce error into the finite helical axis calculation [8]. A two-tailed paired Student *t*-test was used to compare the moment arms between elastic and inertial loading conditions at 5 degree increments during both the knee extension and flexion phases (Fig. 1c).

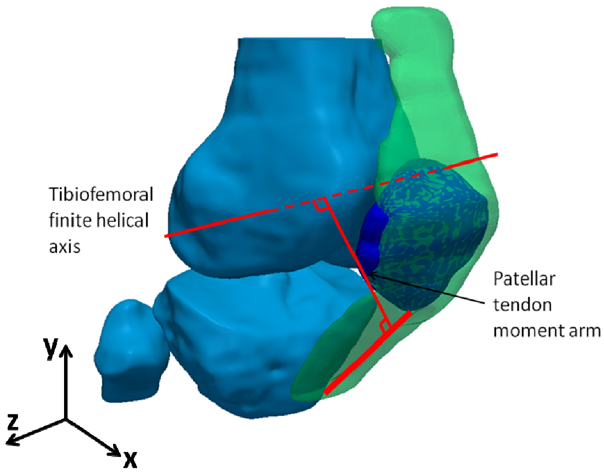

Figure 2: The patellar tendon moment arm was the shortest distance between the tendon's line of action and the tibiofemoral finite helical axis.

RESULTS AND DISCUSSION

Patellar tendon moment arms varied significantly with loading. During the knee extension phase, the inertial load induced a significantly smaller moment arm than elastic loading between 20 and 40 degrees of knee flexion, with differences ranging from 14-34% at angles where at least seven subjects were represented (Fig. 3). Similar results were seen during the flexion phase. The load-dependent variation in moment arms can arise from changes in patellofemoral kinematics and/or tibiofemoral kinematics. Further analysis revealed that the FHA in the inertial case was significantly more anterior (~5 mm) near full knee flexion, thereby contributing to the decreased moment arm. Anterior translation of the tibia due to quadriceps activity with knee flexion likely induced this change [9].

The quadriceps undergo lengthening contractions during the loading phase of gait, making the inertial case relevant to consider in the context of functional movement. The inertial loads used in this study induced peak knee extension moments of ~0.5 Nm/kg [9], which is comparable to that seen in the loading phase of gait [10]. Hence, a reduction in the patellar tendon moment arm could necessitate greater muscle forces during gait than would be estimated using kinematic knee models [1]. Further analysis is required to determine the net effect on knee cartilage contact patterns, given that articular surface geometry and ligament stretch are also important to consider.

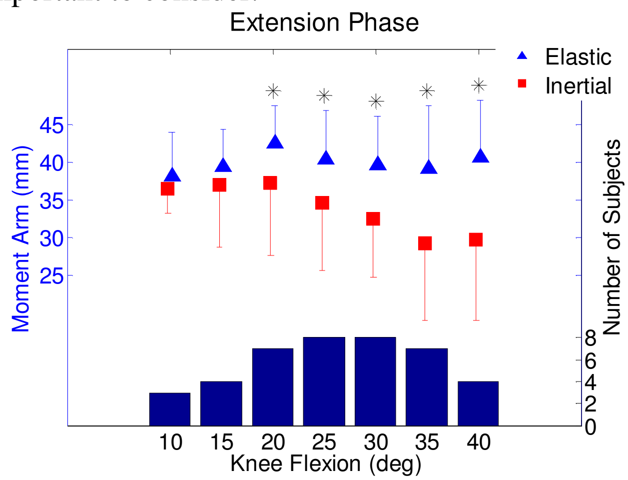

Figure 3: Patellar tendon moment arms for elastic and inertial loads. *p<0.05 for load effect

CONCLUSIONS

Eccentric loading of the quadriceps can reduce the patellar tendon moment arm, which may be important to consider when using models to estimate internal knee loads during locomotion.

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