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Short communication

In vivo assessment of the interaction of patellar tendon tibial shaft angle and anterior cruciate ligament elongation during flexion

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ABSTRACT

A potential cause of non-contact anterior cruciate ligament (ACL) injury is landing on an extended knee. In line with this hypothesis, studies have shown that the ACL is elongated with decreasing knee flexion angle. Furthermore, at low flexion angles the patellar tendon is oriented to increase the anterior shear component of force acting on the tibia. This indicates that knee extension represents a position in which the ACL is taut, and thus may have an increased propensity for injury, particularly in the presence of excessive force acting via the patellar tendon. However, there is very little *in vivo* data to describe how patellar tendon orientation and ACL elongation interact during flexion. Therefore, this study measured the patellar tendon tibial shaft angle (indicative of the relative magnitude of the shear component of force acting via the patellar tendon) and ACL length *in vivo* as subjects performed a quasi-static lunge at varying knee flexion angles. Spearman rho rank correlations within each individual revealed that flexion angles were inversely correlated to both ACL length (rho = −0.94 ± 0.07, mean ± standard deviation, $p < 0.05$) and patellar tendon tibial shaft angle (rho = −0.99 ± 0.01, $p < 0.05$). These findings indicate that when the knee is extended, the ACL is both elongated and the patellar tendon tibial shaft angle is increased, resulting in a relative increase in anterior shear force on the tibia acting via the patellar tendon. Therefore, these data support the hypothesis that landing with the knee in extension is a high risk scenario for ACL injury.

1. Introduction

Anterior cruciate ligament (ACL) injuries primarily affect a young and active population (Gilchrist et al., 2008; Griffin et al., 2006), with an estimated 400,000 injuries reported in the United States each year (Kibler, 2009). In addition to the acute consequences of injury, long-term effects such as post-traumatic osteoarthritis (Lohmander et al., 2007) can severely affect quality of life. Therefore, injury prevention is critical (Gilchrist et al., 2008; Pfeiffer et al., 2006; Steffen et al., 2008; Stevenson et al., 2015). Research targeted at understanding movements that present a high risk for ACL injury may inform training programs to improve injury prevention.

A scenario that may represent a high risk for ACL injury is landing on an extended knee (Cochrane et al., 2007; DeFrate et al., 2007; Malinzak et al., 2001). In support of this mechanism, *in vivo* studies have shown that the ACL is elongated when the knee is extended (Englander et al., 2018; Lamontagne et al., 2008; Li et al., 2005; Taylor et al., 2013; Taylor et al., 2011; Utturkar et al., 2013). Therefore, these studies suggest that knee extension represents a position in which the ACL is taut, and thus may have an increased propensity for injury, particularly in the presence of excessive anterior shear force acting on the tibia.

Furthermore, previous studies have investigated the orientation of the patellar tendon relative to the tibia as a function of flexion (DeFrate et al., 2007; Nunley et al., 2003). Specifically, these studies have shown that when the knee is positioned at a low flexion angle, the attachment site of the patellar tendon on the patella is oriented anterior to its attachment on the tibia. Therefore, at low flexion angles, the patellar tendon is positioned to increase the relative magnitude of the shear component of forces acting on the tibia, which may increase loading on the ACL (Butler et al., 1980). Thus, *in vivo* data describing how ACL elongation interacts with the orientation of the patellar tendon during the flexion path

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would further the understanding of this mechanism of injury. To address this question, the present study obtained *in vivo* measurements of the orientation of the patellar tendon as well as the length of the ACL as subjects performed a single legged quasi-static lunge at varying knee flexion angles.

2. Materials and methods

Eight healthy male subjects (mean age 26.5 ± 5.5 years) with no previous history of lower extremity injury or surgery prior to testing were evaluated using an IRB approved protocol. One knee from each subject (6 right, 2 left) was imaged using a 3 T magnetic resonance imaging (MRI) scanner (Trio Tim, Siemens Medical Solutions USA, Malvern, PA). Sagittal, coronal, and axial images were acquired from the subjects while lying supine, using a double-echo steady-state sequence (DESS) and an eight-channel knee coil (resolution: $0.3 \times 0.3 \times 1$ mm; flip angle: 25°, repetition time: 17 ms, echo time: 6 ms). Outlines of the femur, tibia, patella, and the footprints of the ACL and patellar tendon attachment sites, were segmented manually using solid-modeling software (Rhinoceros 4.0, Robert McNeel and Associates, Seattle, WA) (Fig. 1A). These segmentations were compiled into 3D models of the joint (Fig. 1B, C) (Kim et al., 2015; Li et al., 2005; Utturkar et al., 2013; Widmyer et al., 2013). The positions and shapes of the ligament attachment sites were confirmed in the three orthogonal imaging planes. Prior validation studies have demonstrated that this approach can locate the center of the ACL footprint to within 0.3 mm (Abebe et al., 2009; Taylor et al., 2013).

Following MRI, each subject's knee was imaged from two orthogonal directions using biplanar fluoroscopes (BV Pulsera, Philips, The Netherlands) (Li et al., 2005), each with an image resolution of 1024×1024 pixels^2. The subject posed in a single legged static lunge position at various flexion angles. For each pose, subjects were guided on how to position their knee with a goniometer. The orthogonal fluoroscopic images were then imported into the solid-modeling software and positioned to recreate the biplanar fluoroscopic imaging setup. The 3D MRI knee model was subsequently imported into this reconstructed environment. The model of each bone was moved separately within 6 degrees of freedom until its projections onto the two imaging planes from the perspective of the fluoroscopic sources matched the outlines of bones as seen in the fluoroscopic images. Therefore, the *in vivo* positions of the bones during the lunges were reproduced (DeFrate et al., 2007; Taylor et al., 2013; Taylor et al., 2011; Utturkar et al., 2013) (Fig. 1D). Previous validation has shown that this method can measure 3D kinematics to within 0.1 mm and 0.3° (Caputo et al., 2009; DeFrate et al., 2006).

After positioning the bones appropriately, knee joint angles (flexion angle and patellar tendon tibial shaft angle) and the length of the ACL were measured (DeFrate et al., 2007; Utturkar et al., 2013) (Fig. 2). Flexion angle represents the angle between the long axes of the femur and tibia about the femoral transepicondylar axis (Fig. 2A). Patellar tendon tibial shaft angle represents the angle between the long axis of the tibia and the line of action of the patellar tendon (represented by a line connecting the centroid of its attachment site footprints on the patella and tibia) measured in the sagittal plane (Fig. 2B). Positive angles indicate that the patellar tendon attachment site on the patella is oriented anterior to its attachment site on the tibia (Nunley et al., 2003). ACL length was measured as the centroid to centroid distance between the footprints of the femoral and tibial attachment sites. All

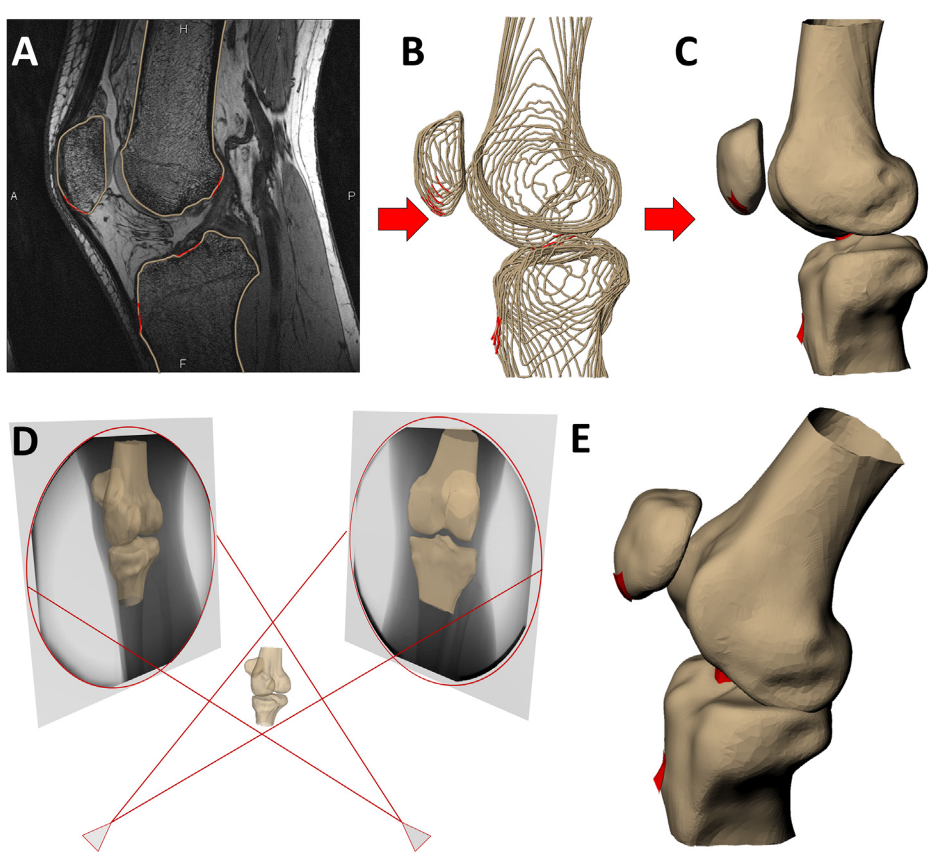

Fig. 1. (A) Outer margins of the femur, tibia, patella, and ligament attachment sites were outlined on the MR images. (B) The contours were compiled into wireframe models. (C) 3D mesh models were created from the wireframe models. (D) The bone models were positioned to match the fluoroscopic images captured during the lunges. (E) The matched models reproduce the *in vivo* position of the joint during each quasi-static lunge.

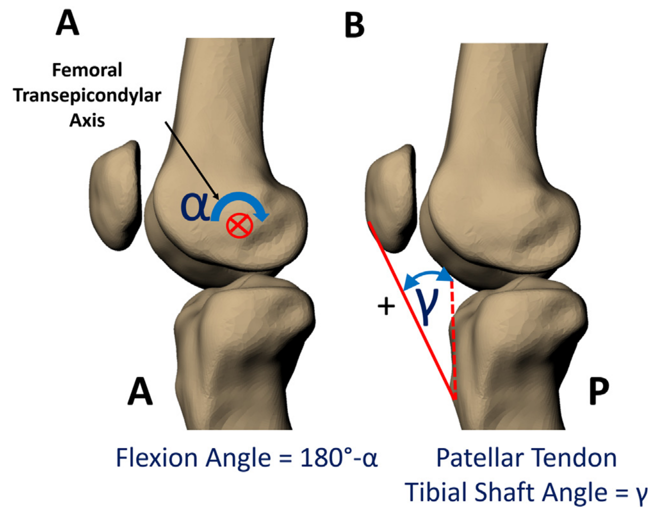

Fig. 2. Knee joint angles (in degrees) were determined using a standardized coordinate system based on bony anatomy. (A) Flexion angle represents the angle between the long axes of the femur and tibia about the femoral transepicondylar axis. (B) Patellar tendon tibial shaft angle represents the angle between the long axis of the tibia and the line of action of the patellar tendon (represented by a line connecting the midpoints of its attachment site footprints on the patella and tibia) measured in the sagittal plane.

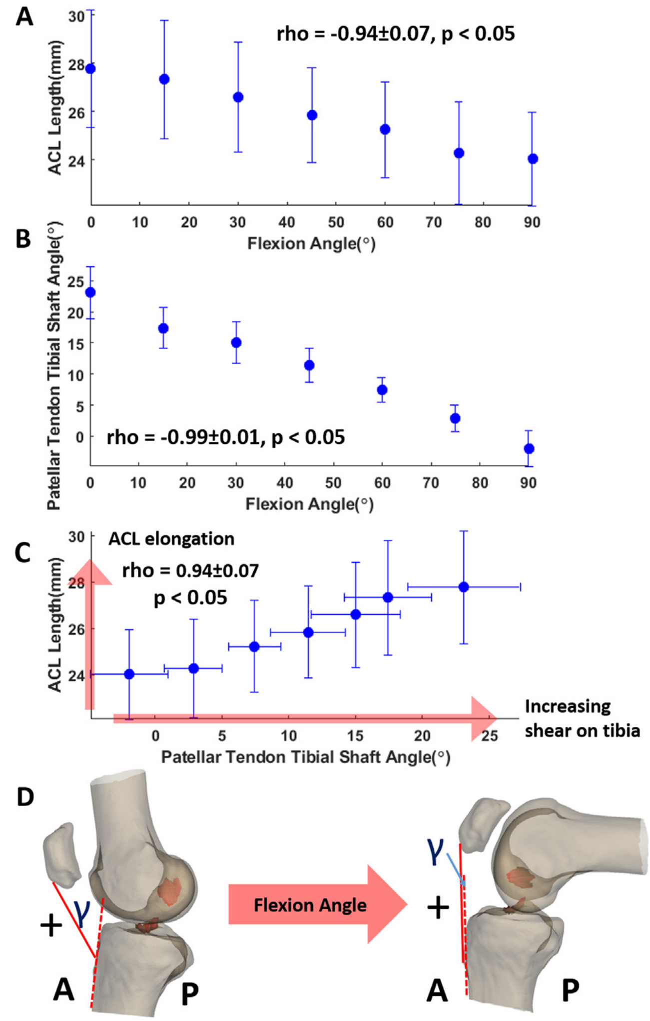

Fig. 3. (A) ACL length was inversely correlated with flexion angle. (B) Patellar tendon tibial shaft angle was also inversely correlated with flexion angle. (C) Patellar tendon tibial shaft angle was significantly correlated with ACL length. (D) Example of the patellar tendon tibial shaft angle with the knee in extension and in flexion for one subject.

measurements were linearly interpolated from the data to represent values of each variable at flexion angles between 0° and 90° in increments in of 15°.

Statistics were performed using Matlab (Mathworks, Natick, MA) with a significance level of $p < 0.05$. Spearman rho rank correlations were performed between the variables (ACL length, flexion angle, and patellar tendon tibial shaft angle) for each subject individually. Means and standard deviations of the correlation coefficients across individuals are reported.

3. Results

ACL length decreased linearly with flexion angle, ranging from an average of 27.8 ± 2.4 mm at 0° of flexion to an average of 24.0 ± 1.9 mm at 90° of flexion (mean ± standard deviation). Furthermore, patellar tendon tibial shaft angle also decreased with flexion angle, ranging from $23.1 \pm 4.2°$ at 0° of flexion to $-1.9 \pm 2.9°$ at 90° of flexion. Spearman rho rank correlations within each individual revealed that flexion angles were inversely correlated to both ACL length (rho = -0.94 ± 0.07, Fig. 3A) and patellar tendon tibial shaft angle (rho = -0.99 ± 0.01, Fig. 3B), all with $p < 0.05$. Furthermore, patellar tendon tibial shaft angle and ACL length were highly correlated within each subject individually, with the mean of these correlation coefficients across subjects being rho = 0.94 ± 0.07, all with $p < 0.05$.

4. Discussion

The present study used biplanar fluoroscopic imaging in combination with 3D models of the knee joint to measure *in vivo* ACL elongation, patellar tendon tibial shaft angle, and knee flexion angle. The findings of this study indicate that the patellar tendon tibial shaft angle, which is indicative of the relative magnitude of the shear component of force acting via the patellar tendon, and the length of the ACL are maximized as the knee is extended.

The relationship between flexion angle and ACL length observed in this study is in line with previous data regarding *in vivo* ACL function (Englander et al., 2018; Li et al., 2005; Taylor et al., 2013; Taylor et al., 2011; Utturkar et al., 2013). For example, (Li et al., 2005) measured ACL length during knee flexion, and also determined that the length of the ACL decreased with increased flexion. Furthermore, (Utturkar et al., 2013) measured ACL length for various static knee postures, including the knee at full extension and at 30° of flexion. It was found that the ACL was significantly longer with the knee positioned in extension as compared to when the knee was flexed at 30°. Furthermore, ACL strain during dynamic activities such as jump landing (Taylor et al., 2011) and gait (Englander et al., 2018; Taylor et al., 2013) have been characterized *in vivo*. These studies have found that while different loading conditions may influence ACL function, in general ACL strain is at its peak when knee flexion is minimal throughout these dynamic activities. Finally, these findings are also congruent with studies that have used arthroscopically implanted strain gauges (Beynnon et al., 1992; Cerulli et al., 2003; Fleming et al., 2001; Lamontagne et al., 2008), which also demonstrate ACL elongation with knee extension.

Furthermore, the significant inverse correlation between flexion angle and patellar tendon tibial shaft angle observed in this study is congruent with prior data that shows that the patellar tendon is aligned to generate anterior shear forces on the tibia when the knee is positioned at a low flexion angle (DeFrate et al., 2007; Nunley et al., 2003). The more positive the patellar tendon tibial shaft angle, the more anterior the patellar tendon attachment on the patella is relative to its attachment on the tibia (Fig. 2B). At higher flexion angles, the patellar tendon tibial shaft angle is negative, and the patellar tendon is aligned to pull posteriorly on the tibia, thereby reducing anterior shear forces and loading on the ACL. Importantly, the strong inverse correlation between flexion angle and patellar tendon tibial shaft angle observed in this study (Fig. 3B) and others (DeFrate et al., 2007; Nunley et al., 2003) indicates that when the knee is extended, vulnerability to ACL failure resulting from ACL elongation is compounded by the increased relative magnitude of anterior shear forces on the tibia acting via the patellar tendon.

Additionally, prior studies have indicated that quadriceps activation may be a main component of anterior shear loading of the ACL when the knee is positioned at a low flexion angle. Specifically, multiple studies in cadavers have observed anterior tibial translation in response to anterior shear forces caused by simulated quadriceps loading with the knee positioned at low flexion angles (Arms et al., 1984; Berns et al., 1992; DeMorat et al., 2004; Draganich and Vahey, 1990). Also to this point, a study using kinematic analysis, electromyography (EMG), and inverse dynamics to estimate joint forces and moments found that an important component of anterior tibial shear force included the integrated EMG activity of the vastus lateralis during a stop jump task (Sell et al., 2007). Furthermore, another EMG study suggested that greater pre-activity of the rectus femoris predicted increased peak external anterior shear force during single legged landings (Brown et al., 2014). Thus, these studies provide evidence for the hypothesis that the risk for a non-contact ACL injury increases when the knee is positioned close to extension, due to increased anterior shear forces on the tibia originating from the quadriceps. In line with this hypothesis, analysis of bone bruise patterns in patients with ACL injury have indicated that substantial anterior tibial translation may occur at the time of ACL injury, with the knee positioned at a low flexion angle (Kim et al., 2015; Owusu-Akyaw et al., 2018). Taken together with evidence from the present study, these findings suggest that in the case of a perturbation in normal motion patterns when the knee is positioned at a low flexion angle, there may be an increased likelihood of ACL injury due to the anterior shear loading on an already elongated ACL.

Future work toward understanding ACL injury mechanisms may include measurements of ACL elongation and patellar tendon orientation during dynamic activity (Englander et al., 2018; Miranda et al., 2011; Myers et al., 2011), further elucidating the motions that result in increased ACL loading (Taylor et al., 2011). Furthermore, consideration of the influence of posterior tibial slope may further improve understanding ACL injury risk (Marouane et al., 2014; Marouane et al., 2015). Finally, the inclusion of female subjects in addition to males may improve understanding of sex-based differences in ACL injury risk (Arendt et al., 1999).

To summarize, the results of this study show that the ACL is both elongated and the patellar tendon is oriented to increase the anterior shear component of force acting on the tibia when the knee is extended. Therefore, these findings support the hypothesis that landing with an extended knee is a scenario that puts the ACL at high risk for rupture (Cochrane et al., 2007; Griffin et al., 2006; Malinzak et al., 2001; Yu and Garrett, 2007). Further research aimed at understanding factors that may increase the likelihood of an individual to utilize high risk motions during activity may be beneficial toward improving injury prevention.

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Conflict of Interest Statement

The authors of this manuscript have no conflicts of interest pertaining to this work to disclose.

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