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Orientation of tendons in vivo with active and passive knee muscles

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Abstract

Tendon orientations in knee models are often taken from cadaver studies. The aim of this study was to investigate the effect of muscle activation on tendon orientation in vivo. Magnetic resonance imaging (MRI) images of the knee were made during relaxation and isometric knee extensions and flexions with 0°, 15° and 30° of knee joint flexion. For six tendons, the orientation angles in sagittal and frontal plane were calculated. In the sagittal plane, muscle activation pulled the patellar tendon to a more vertical orientation and the semitendinosus and sartorius tendons to a more posterior orientation. In the frontal plane, the semitendinosus had a less lateral orientation, the biceps femoris a more medial orientation and the patellar tendon less medial orientation in loaded compared to unloaded conditions. The knee joint angle also influenced the tendon orientations. In the sagittal plane, the patellar tendon had a more anterior orientation near full extension and the biceps femoris had an anterior orientation with 0° and 15° flexions and neutral with 30° flexions. Within 0° to 30° of flexion, the biceps femoris cannot produce a posterior shear force and the anterior angle of the patellar tendon is always larger than the hamstring tendons. Therefore, co-contraction of the hamstring and quadriceps is unlikely to reduce anterior shear forces in knee angles up to 30°. Finally, inter-individual variation in tendon angles was large. This suggests that the amount of shear force produced and the potential to counteract shear forces by co-contraction is subject-specific.

Keywords: Knee; Tendon orientation; Magnetic resonance imaging; Muscle activation; Shear force

1. Introduction

Shear forces in the knee joint can cause injuries (such as anterior cruciate ligament ruptures). The resultant shear forces in the joint depend on the magnitude and direction of external forces and muscle forces. Muscle forces are difficult to measure and therefore usually predicted from biomechanical models. However, the predicted shear force at the joint is sensitive to assumptions regarding the direction of muscle forces.

So far, most knee models (e.g. Blankevoort and Huiskes, 1996; Lloyd and Buchanan, 1996; O'Connor, 1993; Shelburne and Pandy, 1997; Zavatsky and O'Connor, 1992) have used tendon orientation and moment arm data obtained from cadaver studies (Brand et al., 1982; Buford et al., 1997; Herzog and Read, 1993; Spoor and van Leeuwen, 1992). However, the orientation of the tendons and thus the direction of the muscle force might be influenced by muscle activation. Magnetic resonance imaging (MRI) provides the possibility

Abbreviations: ACL; Anterior cruciate ligament; BF; Biceps femoris; GR; Gracilis; MRI; Magnetic resonance imaging; PT; Patellar tendon; SM; Semimembranosus; SR; Sartorius; ST; Semitendinosus; TB; Tibia.

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of examining muscle tendons in vivo. Until recently, it was not possible to examine muscle tendons while the muscles were activated with MRI, because of lengthy data acquisition times (Wretenberg et al., 1996). However, MRI technology has been greatly improved in recent years reducing scanning time significantly. The main purpose of this study was to test the hypothesis that muscle activation will change the orientation of tendons around the knee. A secondary aim was to provide data for 3D biomechanical modeling of the muscles around the knee. Since the knee joint angle also affects tendon orientation (Nisell et al., 1986), the effect of muscle activation was studied at three knee joint angles (0°, 15° and 30°). Larger flexion angles were not possible due to the available MR scanner bore size.

2. Method

2.1. Subjects

Five male and three female subjects participated in this study (Table 1). The right knee of all subjects was scanned using MRI. None of the subjects reported previous injury to or complaints of the knee. The protocol was approved by the conjoint Ethics Board of the University of Calgary and Calgary Health Region. All subjects signed an informed consent before MRI.

2.2. MRI protocol

A 3 T MR scanner (Signa; GE Medical Systems, Waukesha, WI) was used for this study. All imaging was performed using the body coil. Because literature showed a wide range of MRI parameters used to image tendons (e.g. T1-weighted spin-echo: Munshi et al., 2003, T2-weighted spin-echo: El-Dieb et al., 2002; Jaramillo et al., 1994; Major and Helms, 2002, proton density: Jaramillo et al., 1994), a pilot study was done to find the best set-up for knee tendon imaging with the 3 T MRI. The best images were obtained using T1-weighted oblique axial imaging (TR 616 s, TE 14 s, FOV 16 cm, slice thickness 3 mm, matrix 256×192, pixel dim. 0.31×0.31 mm, Echo number 1). T1-weighted images were made in the plane perpendicular to the long axis of the body coil and approximately parallel to the tibia plateau. Thirty-five 3-mm slices were acquired starting at the center of the patella and ending just below the tuberositas tibiae. Each acquisition required either 4.12 or 4.54 min of scanning, depending on the obliquity of the acquired image plane.

2.3. Experimental set-up

Scanning took place with and without activation of the muscles around the knee. The subjects were asked to perform isometric knee extensions and flexions during the scanning. A custom-built loading device (Ronsky, 1994) was modified to allow loading in flexion and extension direction (Fig. 1). A support was placed under the upper leg and the leg was strapped to the board. The foot was placed between two wooden bars, preventing internal and external rotation of the leg. The heel was hung in a rubber band that supported the foot. A non-elastic band was placed over the ventral side of the lower leg near the ankle joint. For isometric knee extensions, the subject was asked to lift the lower leg until the band over the ventral side of the ankle became taut, without really pushing against it. At this point, the foot was still partly resting in the rubber band. Therefore, the subject lifted only a part of the weight of the lower leg. The entire weight would have been too large to maintain for the duration of the task. For isometric flexions, the subject was asked to push the heel downward, thereby stretching the rubber band, until the heel just touched the wooden frame. The change of length of the rubber band (in both the extension and the flexion loading) was approximately 17.5 mm, corresponding to a load change of 8.7 N. We assumed that the force on the ventral non-elastic band in extension, and on the wooden frame in flexion could be neglected. By multiplying the 8.7 N by the moment arm of the load, the flexion and extension

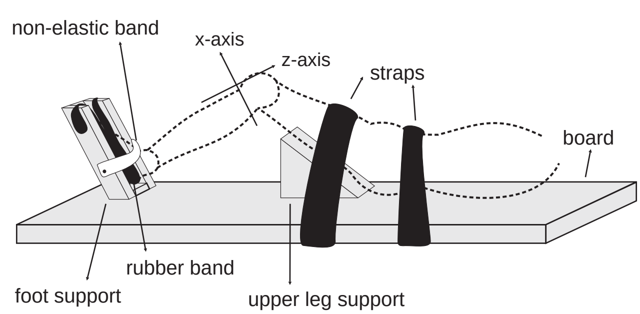

Fig. 1. Schematic overview of the loading device used in the MRI.

Table 1
Subject characteristics (average ± standard deviation)

	Sex (m/f)	Age (yr)	Height (cm)	Weight (kg)	Leg length (cm)	Lower leg length (cm)	Knee width (cm)
Subjects	5/3	26.1 ± 5.3	171.4 ± 3.7	68.9 ± 4.9	83.5 ± 4.9	44.9 ± 2.2	9.8 ± 0.5