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The influence of prior hamstring injury on lengthening muscle tissue mechanics

Amy Silder[a], Scott B. Reeder[a,b,c,d], Darryl G. Thelen[a,e,f,*]

[a] Department of Biomedical Engineering, University of Wisconsin-Madison, Madison, WI, USA
[b] Department of Radiology, University of Wisconsin-Madison, Madison, WI, USA
[c] Department of Medical Physics, University of Wisconsin-Madison, Madison, WI, USA
[d] Department of Medicine, University of Wisconsin-Madison, Madison, WI, USA
[e] Department of Mechanical Engineering, University of Wisconsin-Madison, Madison, WI, USA
[f] Department of Orthopedics and Rehabilitation, University of Wisconsin-Madison, Madison, WI, USA

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ABSTRACT

Hamstring strain injuries often occur near the proximal musculotendon junction (MTJ) of the biceps femoris. Post-injury remodeling can involve scar tissue formation, which may alter contraction mechanics and influence re-injury risk. The purpose of this study was to assess the affect of prior hamstring strain injury on muscle tissue displacements and strains during active lengthening contractions. Eleven healthy and eight subjects with prior biceps femoris injuries were tested. All previously injured subjects had since returned to sport and exhibited evidence of residual scarring along the proximal aponeurosis. Subjects performed cyclic knee flexion–extension on an MRI-compatible device using elastic and inertial loads, which induced active shortening and lengthening contractions, respectively. CINE phase-contrast imaging was used to measure tissue velocities within the biceps femoris during these tasks. Numerical integration of the velocity information was used to estimate two-dimensional tissue displacement and strain fields during muscle lengthening. The largest tissue motion was observed along the distal MTJ, with the active lengthening muscle exhibiting significantly greater and more homogeneous tissue displacements. First principal strain magnitudes were largest along the proximal MTJ for both loading conditions. The previously injured subjects exhibited less tissue motion and significantly greater strains near the proximal MTJ. We conclude that localized regions of high tissue strains during active lengthening contractions may predispose the proximal biceps femoris to injury. Furthermore, post-injury remodeling may alter the in-series stiffness seen by muscle tissue and contribute to the relatively larger localized tissue strains near the proximal MTJ, as was observed in this study.

1. Introduction

Acute muscle strain injuries are frequent in sporting activities, with hamstring injuries particularly common among athletes who sprint regularly. It is well established that muscle is most susceptible to injury during active lengthening contractions (Lieber et al., 1991a, b; Friden and Lieber, 2001; Kirkendall and Garrett, 2002). Correspondingly, hamstring injuries are thought to occur during the late swing phase of sprinting (Heiderscheit et al., 2005; Thelen et al., 2005a, b), when the hamstrings are active, lengthening, and subjected to large inertial loads (Simonsen et al., 1985; Mann et al., 1986). Hamstring injuries most commonly involve the proximal musculotendon junction (MTJ) of the biceps femoris long head (BFLH) (Schneider-Kolsky et al., 2006; Verrall et al., 2006; Koulouris et al., 2007; Silder et al., 2008).

In-situ animal studies have shown that acute strain injuries do not involve an actual separation between muscle and tendon, but rather the muscle tissue adjacent to the MTJ is damaged (Garrett et al., 1987). Following injury, the highly vascularized muscle tissue quickly begins regenerating (Kaariainen et al., 2000). However, within a week's time, the growth of fibrous tissue begins to prevail over the muscle regeneration process and eventually leads to the presence of mature acellular scar at the site of injury (Nikolaou et al., 1987; Jarvinen et al., 2005). This scar tissue can persist indefinitely, having been found up to 12 months post-injury in animal models (Kaariainen et al., 2000). Similarly,

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* Corresponding author at: Department of Mechanical Engineering, 1513 University Ave., Madison, WI 53706, USA. Tel.: +1 608 262 1902; fax: +1 608 265 2316.
E-mail address: thelen@engr.wisc.edu (D.G. Thelen).

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in humans, magnetic resonance (MR) imaging has shown evidence of scar tissue up to one year following an athlete's return to sport (Silder et al., 2008). The presence of scar tissue can alter muscle force transmission paths (Huijing, 2003) and may decrease the compliance of the tendon/aponeurosis complex. This, in turn, could change the deformation patterns within muscle tissue. Given the links between tissue strain magnitudes and injury risk observed in animal models (Lieber and Friden, 1993), one concern would be an increase in localized tissue strains adjacent to the fibrous scar. Such an effect, if present, may contribute to the high re-injury rates (∼30%) that are observed when athletes return to sport following an acute hamstring injury (Orchard and Best, 2002; Woods et al., 2004).

The purpose of this study was to assess the influence of prior hamstring injury on *in-vivo* muscle deformation patterns during active lengthening contractions. Dynamic MR imaging techniques (Pappas et al., 2002; Asakawa et al., 2003; Finni et al., 2003) were used to track biceps femoris muscle tissue displacements during a knee flexion–extension task that included active lengthening hamstring contractions. Tissue displacement data were spatially differentiated to estimate two-dimensional strain distributions (Zhou and Novotny, 2007; Zhong et al., 2008). Muscle tissue strains were then used to address two specific research aims. First, we tested the hypothesis that the largest tissue strains would be observed along the proximal MTJ, where muscle injury is commonly observed. Second, we examined the effects of residual scar tissue on neighboring muscle tissue strain by comparing a group of uninjured athletes to those with prior hamstring injuries.

2. Methods

2.1. Subjects

The right limbs of 11 healthy subjects (5 males, 6 females; age 31 ± 11 y; height 1.77 ± 0.09 m; mass 70 ± 9 kg) and the previously injured limbs (left or right) of eight subjects (6 males, 2 females; age 23 ± 6; height 1.80 ± 0.10 m; mass 75 ± 11 kg) were evaluated. Subject questioning and clinical reports confirmed that all previously injured subjects sustained at least one proximal biceps femoris injury, with six of the eight reporting one or more re-injuries in the same location. Three subjects had a history of bilateral hamstring injuries. For these subjects, dynamic imaging was performed on the limb that was more severely injured, as assessed by total time from sport (Slavotinek et al., 2002). Informed consent was obtained prior to testing according to a protocol approved by the University of Wisconsin's Health Sciences Institutional Review Board.

We required that all previously injured subjects present with visible remodeling of the proximal biceps femoris tendon/aponeurosis (Fig. 1). The presence of post-injury remodeling was assessed by collecting high resolution static images of both limbs using an investigational version of a previously described T_1 weighted chemical shift based water–fat separation method known as IDEAL (Iterative Decomposition of water and fat with Echo Asymmetry and Least squares estimation) combined with three-dimensional (3D) spoiled gradient echo (SPGR) imaging (Reeder et al., 2007). IDEAL provides water-only images with uniform suppression of fat-signal over large fields-of-view. All subjects were scanned in a relaxed prone position using a clinical 1.5 T MR scanner (Signa HDx v14.0 TwinSpeed, GE Healthcare, Waukesha, WI, USA). A phased array torso coil was used with the following scan parameters: coronal 3D slab, TR=12.5 ms, 3 echoes (1 echo/TR) with TE=4.4, 5.0, 6.6 ms, 15° flip angle; matrix, ±41.7 kHz bandwidth, partial k_y acquisition; 384×256 matrix with 46×46 cm^2 field-of-view with 84 slices, and 1.4 mm slice thickness for a true spatial resolution of $1.2 \times 1.8 \times 1.4$ mm^3 (interpolated to $0.9 \times 0.9 \times 7$ mm^3). Water and fat images were created using homodyne reconstruction performed on-line (Reeder et al., 2005; Yu et al., 2005). The IDEAL image set was used to perform a bilateral comparison of the proximal biceps femoris tendon/aponeurosis. Injury location and residual effects were confirmed if substantial non-uniformity in tendon/aponeurosis size was present between limbs.

2.2. Dynamic imaging protocol

Dynamic images were obtained with the subject lying prone on an MR-compatible device (Fig. 2) (Silder et al., 2009). Foam padding was used to position the hip into ∼15° of flexion. The knee was aligned with a fixed rotation shaft on the device, and the ankle was secured to two leg braces that extended from that shaft. The device was used to guide the limb through ∼30° of sagittal knee motion within the scanner, while imposing either inertial (Fig. 2a) or elastic (Fig. 2b) loads on the hamstrings. In a prior study, we showed that the inertial load induces hamstring muscle activity when the knee is extending, thereby resulting in an active lengthening contraction. In contrast, the elastic load induces hamstring activity when the knee is flexing, such that the hamstrings are relaxing and lengthening while the knee is extending (Silder et al., 2009). To reduce fatigue effects, elastic and inertial load magnitudes were kept relatively low, with knee flexion moments varying cyclically between 0 and ∼12 Nm. Peak moments occurred near maximum knee extension in the inertial case and near maximum knee flexion in the elastic case (Silder et al., 2009).

Fig. 1. High resolution static images were obtained for all subjects and used to assess bilateral asymmetries in hamstring morphology. This example shows the visible differences in tendon/aponeurosis morphology at the site of prior injury that was evident for all of the previously injured subjects.

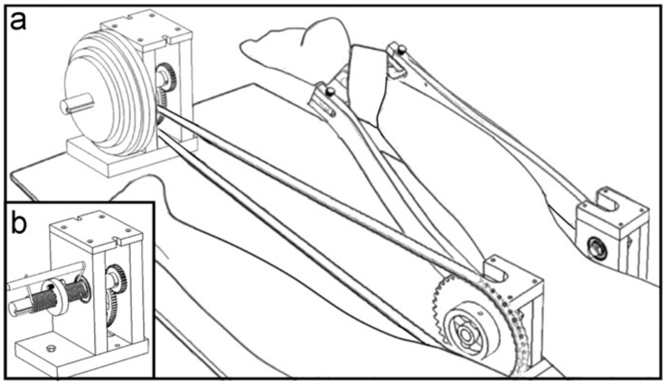

Fig. 2. A MR-compatible device was used during dynamic MR-imaging. Subjects lay prone on the device, with their knee joint aligned with a fixed rotation shaft on the device. The ankle was secured to two leg braces that extend from the shaft. This device was designed to guide the limb through cyclic knee flexion–extension, while imposing (a) inertial or (b) elastic loads on the hamstrings. The inertial loads were imposed using high density inertial disks and induced an active lengthening contraction.