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The effects of aponeurosis geometry on strain injury susceptibility explored with a 3D muscle model ☆

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ABSTRACT

In the musculoskeletal system, some muscles are injured more frequently than others. For example, the biceps femoris longhead (BFLH) is the most commonly injured hamstring muscle. It is thought that acute injuries result from large strains within the muscle tissue, but the mechanism behind this type of strain injury is still poorly understood. The purpose of this study was to build computational models to analyze the stretch distributions within the BFLH muscle and to explore the effects of aponeurosis geometry on the magnitude and location of peak stretches within the model. We created a three-dimensional finite element (FE) model of the BFLH based on magnetic resonance (MR) images. We also created a series of simplified models with a similar geometry to the MR-based model. We analyzed the stretches predicted by the MR-based model during lengthening contractions to determine the region of peak local fiber stretch. The peak along-fiber stretch was 1.64 and was located adjacent to the proximal myotendinous junction (MTJ). In contrast, the average along-fiber stretch across all the muscle tissue was 0.95. By analyzing the simple models, we found that varying the dimensions of the aponeuroses (width, length, and thickness) had a substantial impact on the location and magnitude of peak stretches within the muscle. Specifically, the difference in widths between the proximal and distal aponeurosis in the BFLH contributed most to the location and magnitude of peak stretch, as decreasing the proximal aponeurosis width by 80% increased peak average stretches along the proximal MTJ by greater than 60% while slightly decreasing stretches along the distal MTJ. These results suggest that the aponeurosis morphology of the BFLH plays a significant role in determining stretch distributions throughout the muscle. Furthermore, this study introduces the new hypothesis that aponeurosis widths may be important in determining muscle injury susceptibility.

1. Introduction

Some skeletal muscles are injured more commonly than others (Garrett, 1999); however, the factors making certain muscles more injury prone are not well understood. For example, amongst the bilateral hamstring muscles, the biceps femoris longhead (BFLH) is injured most frequently, accounting for approximately 80% of all hamstrings injuries (Armfield et al., 2006). Previous investigations have reported that injury in the BFLH is most often observed along the length of the myotendinous junction (MTJ) in the proximal region of the muscle tissue (Clanton and Coupe, 1998; Koulouris and Connell, 2003; Silder et al., 2008). While these injury patterns are well documented, the underlying mechanisms that give rise to these patterns are not presently understood. It remains unclear why the BFLH is more prone to injury than the other hamstrings muscles and why injuries in the BFLH are generally localized near the proximal MTJ.

Strain injury in skeletal muscle has been thought to result when regions of a muscle experience localized strains above a certain threshold (Garrett, 1999). Those regions have been shown to correspond to the location of injury (Best et al., 1995). Muscles are most prone to injury while performing lengthening contractions (Armstrong et al., 1983; Faulkner et al., 1993; Lieber and Friden, 2002; Noonan and Garrett, 1992; Schwane and Armstrong, 1983) and the magnitude of lengthening strains correlates with the degree of fiber injury (Lieber and Friden, 1993). The BFLH and the other biarticular hamstrings undergo similar lengthening musculotendon strains and loading during running (Thelen et al., 2005b). One possible explanation for the BFLH's increased incidence for injury is that the muscle experiences larger localized strains as compared to the other hamstrings. Since BFLH injuries are more commonly located near the proximal MTJ, the localized strains would also likely be concentrated in this region.

What features of the internal architecture of the BFLH could give rise to large localized strains along the proximal MTJ? The muscle fibers of the BFLH originate along a long, narrow proximal

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aponeurosis and insert along a shorter, broader distal aponeurosis. Previous studies have established that aponeuroses perform important roles during locomotion (Azizi and Roberts, 2009; Roberts et al., 1997) and may also help protect muscles from injury by reducing overall fascicle strains during lengthening contractions (Lemos et al., 2008). While the effects of the aponeurosis on overall fiber stretch have been investigated, little is known about how aponeurosis morphology affects local tissue stretches. In order to investigate the effects of aponeurosis morphology on muscle tissue stretch distributions, a model that incorporates the complex shape and mechanical properties of the aponeuroses and muscle tissue is needed.

The purpose of this study was to build computational models to determine how the aponeurosis dimensions of the BFLH muscle influence stretch distributions in the muscle tissue. In order to determine if the three-dimensional morphology of the muscle gives rise to large stretches localized along the proximal MTJ, we developed a three-dimensional finite element (FE) model of the BFLH based on magnetic resonance (MR) imaging data. We analyzed stretch distributions within the FE model for a simulated activated lengthening condition. We also constructed a simplified BFLH model with muscle architecture and aponeurosis dimensions that matched those of the MR-based model. By varying the aponeurosis width, length, and thickness of the simplified model, we were able to determine how each aponeurosis dimension affects the stretch distributions within the muscle tissue.

2. Methods

2.1. MR-based BFLH model

We reconstructed the surface geometry of the BFLH muscle, proximal aponeurosis, distal aponeurosis, and femur from MR image data (Fig. 1A). A series of axial MR images were acquired of a healthy male subject's upper thigh in a 1.5-T MR scanner (General Electric Healthcare, Milwaukee, WI, USA) with a 3 mm slice thickness (matrix, 512×512; field of view, 400×400 mm^2). Images were acquired over the thigh from the BFLH origin to the BFLH insertion. In all images, the boundaries of the structures of interest were manually outlined using Mimics segmentation software (Mimics 12.0, Materialise NV). Three-dimensional polygonal surface reconstructions were created for each structure based on the axial segmentation data. We created a finite element mesh consisting of approximately 20,000 eight-node hexahedral elements of the BFLH muscle based on these surface reconstructions using the FE mesh generator TrueGrid (XYZ Scientific Applications, Livermore, CA) (Fig. 1B). Aponeurosis and muscle tissue were constrained to remain attached to one another by defining tied contact interfaces between coinciding nodes (Puso et al., 2006).

In order to define the corresponding fiber geometry for the BFLH model, we used a mapping technique that applies muscle specific fiber architecture to the FE mesh (Blemker and Delp, 2005). The fiber map was defined such that the fibers originated along the proximal aponeurosis and inserted along the distal aponeurosis (Fig. 1C). Based on the fiber map, a fiber direction vector was determined for each element in the mesh to serve as an input to the constitutive model. The average fiber length for the BFLH fiber map was 10.5 cm which agrees well with reported values for the BFLH muscle (Ward et al., 2009).

2.2. Simple BFLH model

In order to explore the effects of aponeurosis morphology on the stretch distributions within the MR-based BFLH model, we constructed a series of simplified finite element models. These models all had a simplified geometry that was based on anatomical measurements from the MR-based model. This approach allowed us to independently isolate the effects of the aponeurosis dimensions on stretches within the muscle tissue.

To define the dimensions of the simple models, we made several measurements from the MR-based BFLH model. The first set of dimensions was the same across all model variations; these included: overall BFLH muscle-tendon length, the lengths of the proximal and distal external tendons, and the average distance between the proximal and distal aponeuroses. The second set of dimensions was used to define the morphology of the aponeuroses in what will be referred to as the "simple BFLH model" (Fig. 2B): aponeurosis length, thickness, and width. We measured proximal and distal aponeurosis lengths of 17.8 and 15.6 cm, respectively. These measurements were in good agreement with published data for the same muscle (Woodley and Mercer, 2005). In order to determine the thickness of the proximal and distal aponeuroses, we measured the aponeurosis thickness on multiple axial MR images. The average thickness along the length of each individual MTJ (Fig. 2A) was used to define the thickness in the simple model (Fig. 2B). The proximal aponeurosis had a measured thickness of approximately 3 mm and the distal aponeurosis was thinner with an average thickness of

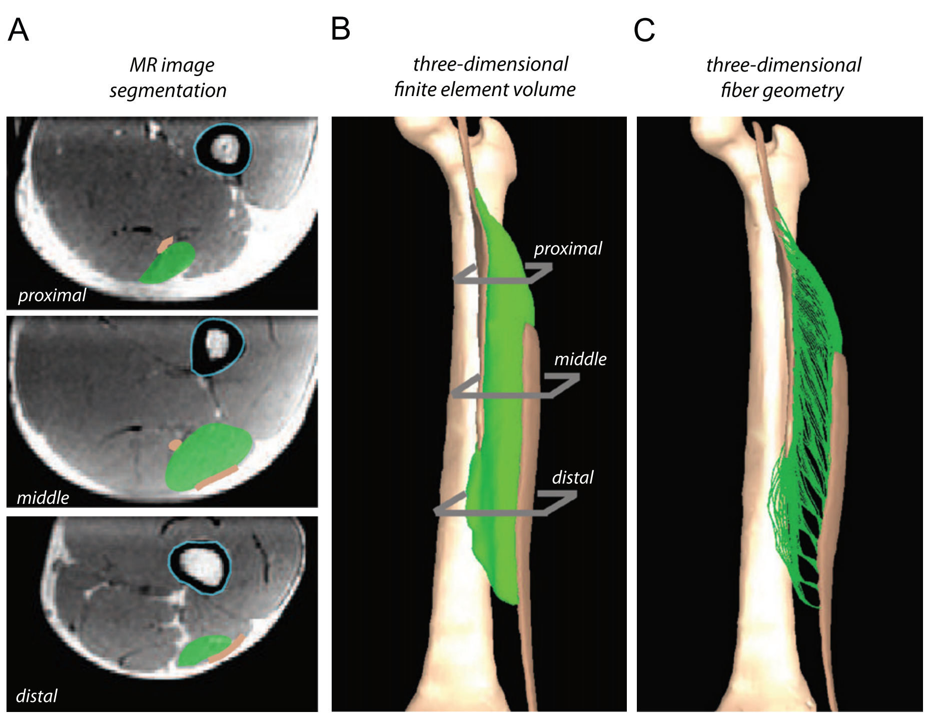

Fig. 1. Methods for constructing three-dimensional finite element models of the BFLH. Models were built from axial magnetic resonance images of the thigh (A). The BFLH (green shaded regions), aponeuroses (brown shaded regions), and femur (light blue outline) were manually outlined in each image. Finite-element meshes (B) of the BFLH and aponeuroses were created from the series of outlines. A representation of the three-dimensional trajectories of fibers (C) was created using a fiber mapping technique. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)