MUSCLE ARCHITECTURE ANALYSIS USING COMPUTATIONAL FLUID DYNAMICS

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INTRODUCTION

The trajectories of skeletal muscle fascicles are critical to their function, and many skeletal muscles across the body have fascicles with highly complex trajectories. Architectural descriptions of muscles account for fascicle trajectories by reporting parameters such as fascicle length, physiological cross-sectional area, and pennation angle. These parameters are typically reported as constants [1], yet it has been shown that some muscles have large distributions of these parameters [2]. Cadaveric studies of muscle architecture can be time-consuming and do not represent young healthy or patient-specific populations, and MRI diffusion tensor imaging (DTI) studies of muscle architecture can suffer from noisy data acquisition [3]. We present a method to calculate architecture parameters from arbitrarily complex muscles automatically using computational fluid dynamics (CFD). This method can be used to map and examine the three-dimensional architecture of a given muscle, and it can also be used as input to 3D finite-element models of muscle [4].

METHODS

Our method of generating fascicle trajectories using CFD analysis consists of three key steps. Step 1 is to create an image-based solid model of the muscle in Autodesk Inventor® (Autodesk Inc.). Step 2 is to export the solid model to Autodesk Simulation CFD® (Autodesk Inc.) and set up the simulation. We set the inlet pressure to 1Pa and the outlet pressure to 0Pa at the regions of fascicle origin and termination. The other surfaces are set to slip boundary conditions (Figure 1a). The fluid is set to be incompressible with a viscosity of 1Pa-s and density of 1g/cm³. This resulted in very low Reynolds numbers (<1) and good convergence.

Incompressible, laminar, viscous, and steady-state flow are prescribed. These conditions along with the boundary conditions help satisfy the observations about fascicle trajectories in muscle [3]: i) they are coaxially aligned and do not cross each other (viscous flow) ii) they do not branch (incompressible flow) iii) they will not reverse their directions abruptly (laminar flow) and iv) they must connect between attachment points (boundary conditions).

Step 3 is to export the flow direction vectors from the CFD mesh into Matlab (Mathworks Inc.) to perform fascicle and pennation angle analysis. The fascicles are traced and their length distributions are computed (Figure 1b). In addition, pennation angle distributions are calculated using a tendon vector specification from the distal tendon, as in [1] (Figure 1c).

Figure 1: (a) We create image-based models and use CFD to determine muscle architecture parameter distributions for (b) fascicle lengths and (c) pennation angles.
We performed the process on a 2-D image of the adductor brevis [1] and a 3-D MRI-based model of the biceps femoris longhead [5]. We compared the adductor brevis calculations with a previous cadaver study [1].

RESULTS

The mean fascicle length for the 2D adductor brevis model (raw, unadjusted for sarcomere length) was 12.9cm (Figure 2a). This can be compared to the published raw fascicle length average measurements of 11.1cm with standard deviation of 1.53cm across 21 cadavers (10.3 ± 1.42cm optimal fascicle length and 2.91 micron average sarcomere length). The pennation angle distribution ranged from 0 to 17 degrees, with an average of 6.9 degrees (Figure 2a). The cadaver study measured 6.1 degrees mean and 3.1 degrees standard deviation averaged across cadavers.

The CFD solution for the 3D biceps femoris longhead model computed realistic fascicle trajectories and enabled automatic calculations of the fascicle length and 3D pennation angle distributions (Figure 2b).

DISCUSSION

We have proposed a method using computational fluid dynamics to automatically compute muscle architecture parameters and their distributions within the muscle. The method leverages the power of CFD solvers and also enables efficient fascicle mapping for finite-element studies of muscle. The advantages of this method over other methods include ease of implementation and objective, efficient calculation of 3D muscle architecture parameters. Flow guiding surfaces can be incorporated so that complex observed features such as twisting or MRI-DTI data can be incorporated. One limitation of this method is that the fascicles are measured implicitly from the geometry of the muscle and not directly measured. However, the close correlation of the direct cadaver measurements with our computational measurements for the adductor brevis provides preliminary validation of the method. This method has great potential to enhance and empower in vivo architecture studies (e.g., using MRI) on arbitrarily complex muscle geometries.

REFERENCES


Figure 2: (a) Mean muscle architecture parameters calculated with CFD compare favorably with those in a previous cadaver study [1]. (b) CFD computes realistic fascicle trajectories and fascicle length and pennation angle distributions in 3D.