A THREE-DIMENSIONAL MESH WRAPPING MODEL OF THE GLUTEUS MAXIMUS

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INTRODUCTION

The use of commercial and open-source interactive musculoskeletal modeling software has allowed for greater understanding into the function muscles play in locomotion; for example, the role of the gluteus maximus. Early and current models make simplified assumptions, such as utilizing single line segments from origin to insertion or line-independent wrapping techniques. In 2005, Blemker, et al. [1] developed a highly sophisticated finite-element model of the gluteus maximus [2, 3]. It is considered a gold-standard by the authors.

Although Blemker & Delp's model has demonstrated accuracy, it requires substantial resources and computational energy to create. In addition, it is not compatible with any musculoskeletal modeling programs, such as OpenSim. Therefore, there is a need for an intermediate model, wherein not only are its moment arm (MA) estimates accurate, but it can also be used clinically, in programs like OpenSim.

The objectives of this work were to: 1) describe our mesh wrapping approach to modeling the gluteus maximus muscle and 2) compare hip extension MA to the wrapping model in OpenSim [2], and a reference model [1] over a 90º range of hip flexion.

METHODS

Our approach introduces muscle fiber lines of action connected both longitudinally and transversely, effectively creating a 2D rectangular grid or mesh of 1D line elements (Figure 1). The origin and insertion points of the gluteus maximus were taken from Arnold, et al. [2] and were linearly interpolated to five longitudinal lines of action rather than three. Five transverse lines were used between origin and insertion. Also, a wrapping sphere, unlike an ellipsoid in Arnold's model, was used. In addition, a sacrotuberous ligament was modeled to help anchor the gluteus maximus.

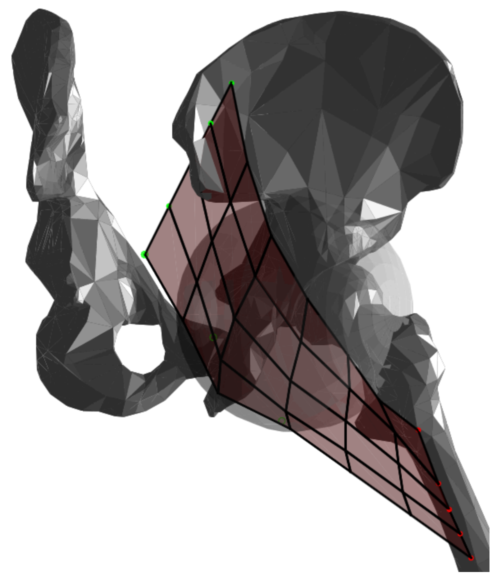

Figure 1. 3D surface plot of the gluteus maximus mesh model (red). Black lines are longitudinal and transverse elements. Wrapping object is the semi-transparent sphere.

Each element was modeled as a linear elastic spring with a stiffness and slack length. Two stiffness values were used: $k_{\text{long}} = 3\times10^6\ \text{N}\cdot\text{m}^{-1}$ and $k_{\text{trans}} = k_{\text{lig}} = 4\times10^6\ \text{N}\cdot\text{m}^{-1}$. Slack lengths were calculated as 75% of the average muscle length over a 0° to 30° flexion range, using the stiffness parameters only. The mesh node coordinates were calculated by minimizing mesh elastic energy and constrained so as not to penetrate the sphere. The mesh was solved from 0° to 90° hip flexion in 2° increments. All calculations were performed in MATLAB.

Muscle length versus flexion angle were extracted and a cubic regression was fit to each line, $\ell_i(\theta)$. Instantaneous MA lengths were calculated analytically [5]:

$$MA_i(\theta) = {d\ell_i}/{d\theta}$$

MAs from Arnold, et al. [2] were exported from OpenSim. In addition, MA ranges reported by Blemker, et al. [1] were obtained using cubic regressions of the reported values. The MA results of Blemker & Delp's finite-element model were presumed to be the most accurate and used as reference [1]. Average root mean square errors (RMSE) were calculated for Arnold's model and our mesh model against Blemker's data for the entire hip flexion range.

RESULTS AND DISCUSSION

The mesh muscle length cubic regression fits were excellent, where for any line, $R_i^2 > 0.999$. The MA results of our model, compared with those of Blemker, et al. [1] and Arnold, et al. [2], can be seen in Figure 2. The total RMSE for our model and Arnold's model relative to Blemker's model can be found in Table 1.

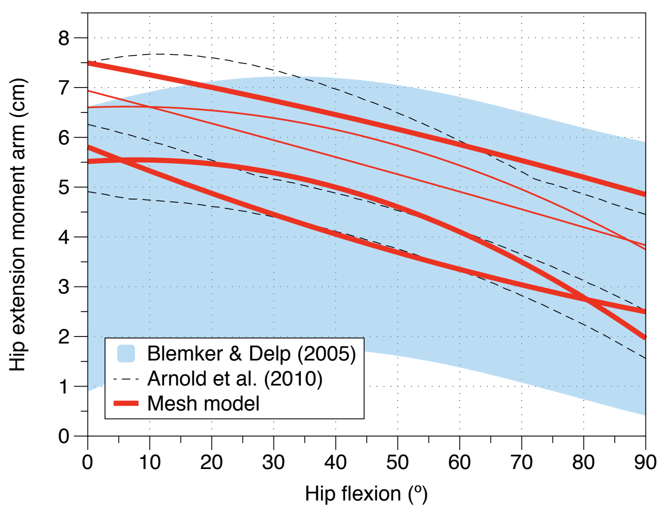

Figure 2. Hip extension moment arms of the gluteus maximus of the mesh model compared to the current OpenSim model [2] and Blemker, et al. [1]'s finite-element model. Bold red lines correspond to Arnold's original three lines of actions.

Based on RMSE values, the interdependent line wrapping model is superior to the independent line wrapping algorithms currently utilized by a standard OpenSim model. As computational power of standard workstations increases, so does the ability to utilize more accurate, higher resolution models. Although finite-element models are still out of reach for routine subject-specific and dynamic modeling, the mesh wrapping approach may be an appropriate stepping-stone for muscles with complex geometries, such as the gluteus maximus.

	RMSE (cm)	**Δ**
Arnold et al. (2010)	0.211	
Mesh model (3 lines)	0.129	−38.83%
Mesh model (5 lines)	0.103	−51.47%

Table 1. RMSE relative to Blemker's model. Mesh model (3 lines) refers to the original three lines utilized by Arnold's model. Δ represents change relative to Arnold's RMSE.

CONCLUSIONS

We have presented a new mesh model for use in musculoskeletal modeling. This gluteus maximus model has decreased the MA error found in a standard OpenSim model by ~40–50% throughout hip flexion. There remains room for improvement and further verification and validation in other planes of motion. The mesh model requires less computational power and resources than finite-element models. By further parameterizing and optimizing our model, it may prove to be an accurate alternative to standard independent line-wrapping models. Future work will explore their utility in dynamic simulations.

REFERENCES

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