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A STREAMLINED MODELING WORKFLOW TO OBTAIN SUBJECT-SPECIFIC MUSCULOSKELETAL MODELS OF LOWER EXTREMITY BASED ON MRI SCAN AND DYNAMOMETRY

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SUMMARY

Subject-specific musculoskeletal models are essential for individual biomechanical applications such as surgical planning or clinical decision making. The aim of this study was to present a streamlined modeling workflow to easily create subject-specific models, based on MRI and dynamometry, in order to obtain reliable model predictions.

INTRODUCTION

Musculoskeletal models represent a promising tool to predict the functional effect of complex orthopedic surgery, such as joint replacements or tendon transfers. Unfortunately, musculoskeletal (MS) geometry and muscle-tendon (MT) architecture, which greatly affect model force predictions, are difficult to measure directly. Moreover, most of these parameters are known to vary with gender, age and activity. Hence, it is essential to generate subject-specific models to achieve reliable force predictions.

Developing efficient methods that allow collecting subject-specific information is a topical challenge. Techniques that allow for capture of the geometry, architecture, motion and mechanics of MS system have already been proposed in the literature [1], but validation of these techniques and their application to biomechanical analysis on a larger scale have not yet been demonstrated.

The aim of this study was to present a streamlined modeling workflow to easily obtain subject specific MS geometry (muscle attachment sites and lines of action, joint center and directions) and MT architecture (tendon slack length, optimal muscle fiber length and maximal isometric muscle force) of the lower extremity, based on MRI and dynamometry. As demonstration, the workflow was applied to a healthy subject, then the outcomes of the obtained subject-specific model were compared with a simple anthropometrically scaled model, in order to investigate the effect of increased subject-specificity on model predictions.

METHODS

SUBJECT-SPECIFIC MODELING WORKFLOW

The proposed streamlined modeling workflow consists of various scaling techniques used to obtain subject-specific MS geometry and MT architecture, based on MRI and dynamometry of the subject analyzed (Figure 1).

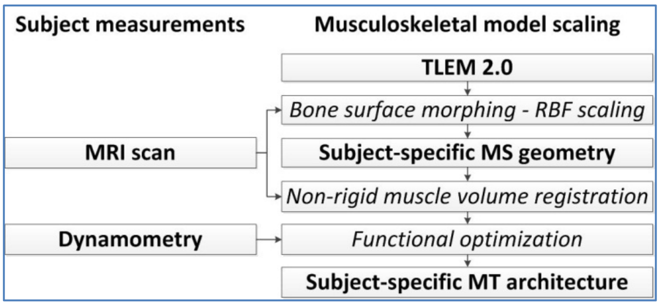

Figure 1: Subject-specific modeling workflow.

SUBJECT MEASUREMENTS

A healthy male subject (age 27, height 1.80m, weight 93 kg) was analyzed. MRI scan of the lower extremities was obtained (3T, T1-weighted, voxel size of 1.0*1.0*3.0mm for pelvis, knee and ankle region, and 1.0*1.0*8.0mm for the remaining upper and lower leg). Moreover, an extensive set of isometric and isokinetic maximal voluntary contractions (MVC) at hip, knee and ankle joints was performed.

TLEM 2.0

We used an updated version of the Twente Lower Extremity Model (TLEM 2.0 [2]) implemented in the AnyBody Modeling System ver. 5.3 (http://www.anybodytech.com/). This new model is based on a consistent set of cadaver measurement and medical imaging data (CT and MRI), including segmented bone surfaces and muscle volumes, coordinates of muscle attachment sites and lines of action, wrapping surfaces, joint centers and axes. TLEM 2.0 is purposely build to be easily morphed into subject-specific models, using the scaling techniques indicated below.

SUBJECT-SPECIFIC MS GEOMETRY

Bone surfaces of pelvis, femur, tibia and fibula were segmented from the MRI scan of the subject using Mimics (http://www.materialise.com/). Rigid registration and automatic morphing from TLEM 2.0 atlas to the subject-specific bone surfaces were applied; then, a non-linear Radial Basis Function (RBF) scaling was used, under the assumption that bony landmarks, muscles attachments sites and lines of action, and joints center and direction follow the morphed bone surface.

SUBJECT-SPECIFIC MT ARCHITECTURE

Initially, muscle volumes were calculated from the MRI scan of the subject, using a non-rigid atlas registration, and maximal isometric muscle force $\boldsymbol{F_0}$ were scaled accordingly. Next, functional optimization of MT architecture was applied, in order to reflect the subject-specific strength profiles measured during the dynamometer tests. Tendon slack length $\boldsymbol{L_T^0}$, optimal muscle fiber length $\overline{\boldsymbol{L_f}}$, and maximal isometric muscle force $\boldsymbol{F_0}$ of MT elements i were optimized under the assumption that muscle activity $\boldsymbol{a}$ necessary to reproduce the measured maximal joint moments is 1 during MVC:

$$\min J\left(\boldsymbol{L_T^0}_i, \overline{\boldsymbol{L_f}}_i, \boldsymbol{F_0}_i\right) = \int_0^T |\boldsymbol{a} - 1|\, dt \qquad (1)$$

MODEL PREDICTIONS

Inverse dynamics and static optimization were used to predict muscle activity during one gait cycle at comfortable speed, for which 3D motion capture and force-plate data were recorded. The performance criterion was to minimize the cubes of muscle activation at each time step.

To investigate the impact of the increased subject-specific MS geometry and MT architecture, muscle activity predictions of the subject-specific models were compared with a simple anthropometrically scaled model, based on the subject's height and weight and the relative positions of optical markers.

RESULTS AND DISCUSSION

Substantial differences were found between anthropometrically scaled and subject-specific bony landmarks and muscle attachment sites, up to 27.53mm for pelvis, 20.76mm for tibia and fibula, and 13.72mm for femur (Table 1). These differences in MS geometry had large effect on the muscle activity predicted during gait (Figure 2). For some muscles, anthropometric scaling caused unrealistic muscle activity predictions (>1), while subject-specific scaling resulted in muscle activity patterns consistent with expected results.

When reproducing measured maximal joint moments, both anthropometric and muscle volume scaling resulted in unrealistic muscle activity much larger than 1, indicating that functional optimization of MT architecture is essential. Substantial differences were found between anthropometrically scaled and subject-specific MT architecture, up to 250% for maximal isometric muscle force $\boldsymbol{F_0}$, and ±10% for tendon slack length $\boldsymbol{L_T^0}$ and optimal muscle fiber length $\overline{\boldsymbol{L_f}}$ (Table 2). These differences in MT architecture had a large effect on the muscle activity predictions during gait (Figure 3).

Table 1: Differences between anthropometrically scaled and subject-specific MS geometry.

Bone segments	**Min** (mm)	**Max** (mm)	**Mean±std** (mm)
Pelvis	0.24	27.53	11.25±5.85
Femur	0.03	13.72	4.50±2.31
Tibia and Fibula	0.16	20.76	10.70±3.53

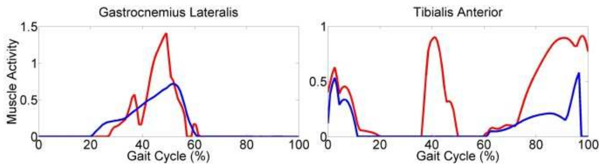

Figure 2: Muscle activity of Gastrocnemius Lateralis (left) and Tibialis Anterior (right) using anthropometric (red) and subject-specific scaling (blue) of MS geometry.

Table 2: Differences between anthropometrically scaled and subject-specific MT architecture of some important muscles.

Muscle	$\boldsymbol{L_T^0}$	$\overline{\boldsymbol{L_f}}$	$\boldsymbol{F_0}$
Biceps Femoris Caput Longum	0.11%	6.94%	27.89%
Gastrocnemius Lateralis	-4.65%	-1.49%	85.81%
Gastrocnemius Medialis	5.56%	0.16%	35.00%
Rectus Femoris	0.07%	-6.94%	149.69%
Semimembranosus	6.92%	-8.59%	214.07%
Soleus Lateralis	-0.43%	-6.85%	18.62%
Soleus Medialis	-5.96%	-0.21%	0.89%
Tibialis Anterior	-0.93%	1.52%	30.01%
Vastus Lateralis	0.69%	1.49%	91.82%
Vastus Medialis	-3.48%	-6.87%	98.63%

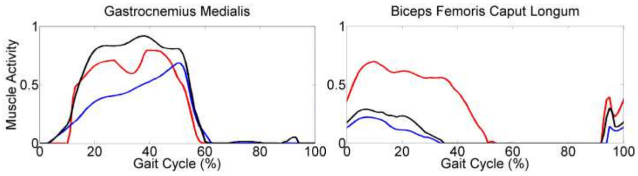

Figure 3: Muscle activity of Gastrocnemius Medialis (left) and Biceps Femoris Caput Longum (right) using anthropometric (red), muscle volumes (black) and functional scaling (blue) of MT architecture.

These large differences in muscle activity predictions can be explained by the fact that the reproduced gait movement could contain some subject-specific information that was captured by the 3D motion tracking and force-plate data, but that was not possible to completely describe using a generic scaled model.

CONCLUSIONS

We presented a streamlined modeling workflow to create subject-specific musculoskeletal models. In this study, a new easily morphable model of the lower extremity was built and combined with subject-specific scaling techniques of MS geometry and MT architecture, based on MRI scan and dynamometry of the subject analyzed. The proposed scaling techniques were successful in achieving more realistic model outcomes, while conventional anthropometric scaling was inadequate and caused unrealistic muscle activity predictions. Using the proposed modeling worflow would permit the reduction of errors in muscle force predictions, hence improving the applicability of subject-specific models and achieving the validity and reliability necessary in surgical scenarios.

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REFERENCES

1. Blemker S, et al, J. Magn Res. Imag.,25:441-451, 2007.
2. Fluit R, et al., CMBBE 2013, Salt Lake City, USA.