ISB 2013 BRAZIL
XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

RESULTS REPEATABILITY OF RIGHT LEG FINITE ELEMENT BASED MUSCULOSKELETAL MODELING

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INTRODUCTION

Musculoskeletal models consists of a set of rigid body segments connected by joints with specified degrees-of-freedom (dof) and spanned muscles and ligaments with specified origins, insertions and pathways. In this paper a non-linear finite element based musculoskeletal workflow is developed to allow the possibility of replacing simplified joint constraints and tissue constructs with realistic 3D data for deformable joints, ligaments and soft tissues when such data is available. The workflow was validated via a human right lower limb model. The model was driven by reflective marker data for walking from 6 subjects (Height 1.74±.06 m, Weight: 70.5±11.7 kg, 3 male & 3 female). Muscle activation outcomes were compared against EMG data reported in literature [4].

METHODS

1. <u>Base Model</u>

A musculoskeletal model of the right leg (Figure 1a) was developed in the Abaqus commercial software using AXIAL connectors for the muscles and JOIN-CARDAN connectors for the joints. Muscle insertion coordinates and muscle parameters were taken from Delp et al. [1]. The model included 43 muscles spanning the hip, knee and ankle joints.

2. <u>Motion Capture</u>

Twelve Qualisys cameras were used to record the spatial position of reflective markers placed on bony landmarks. Four segments of the right leg (Pelvis, Thigh, Shank and Foot) were each tracked by 3-4 markers. The Ground reaction force (GRF) was recorded by 2 force plates embedded in the floor.

3. <u>Musculoskeletal Modeling Implementation</u>

An Isight workflow was developed using Abaqus-based inverse dynamic analysis, python scripts (hill muscle model) and optimization (scaling, positioning and muscle activation) modules. The workflow was divided into four major components-

3(a) <u>Kinematics</u>-

Motion of 3-4 markers on each leg segment was reduced to 6 dofs (3 translations & 3 rotations) for each rigid segment. This step was carried out using a combination of shell element and distributed coupling feature in Abaqus to filter out the skin motion artifact from the motion data.

3(b) <u>Scaling & Positioning</u>-

Subject-specific leg models were developed by scaling and positioning the base model using the first frame of the motion capture data. The Isight optimization module was used to compute the scaling and transformation matrices. The objective function was to minimize the least square error of marker coordinates while hinge constraints were applied at hip, knee and ankle joints.

3(c) <u>Inverse Dynamic Analysis</u>-

An Abaqus analysis was used for inverse dynamics that drives the model by cleaned motion data (Section 3a) and applies GRF on the foot. The analysis outcomes included joint moments, muscle lengths, muscle moment arms and muscle velocities. The range of muscle lengths were used to calibrate the Hill muscle model [2] parameters (fiber length, tendon length) and were set as mean of the range.

3(d) <u>Muscle activation optimization</u>-

A 3-component Hill muscle model [3] was implemented using a Python script that uses the muscle length and muscle velocity as input and computes passive force and maximal muscle force as output. An Isight optimization module was used to estimate muscle activation levels. The objective function was to minimize cubic sum of activations subject to constraints including positive muscle force and moment equilibrium equations for the flexion axis of each joint.

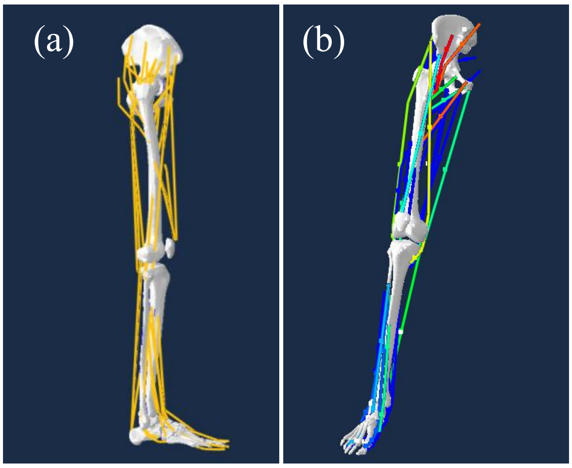

Figure 1: (a) Base Musculoskeletal model of Right leg **(b)** Muscle activation levels (Blue: Low, Red: High) for model driven by walking motion capture data

RESULTS AND DISCUSSION

Subject-specific leg models were developed using the first frame of multiple trials of motion capture data leading to some intra-subject variability in the scaled models. The segment-length variability observed after the scaling and positioning optimization procedure was highest in the thigh and lowest in the foot (Table 1).

Table 1: Intra-subject variability of segment lengths after the scaling and positioning optimization procedure

Subject	Standard Deviation of Segment Lengths		
	Thigh (mm)	Shank (mm)	Foot (mm)
1	8.1	6.4	1.7
2	1.5	4.2	1.3
3	1.0	0.7	0.8
4	1.4	4.9	1.5
5	4.7	1.8	0.5
6	5.3	3.8	1.4
Average	**3.7**	**3.6**	**1.2**

This variability of scaling results can be eliminated by using an alternate workflow that divides the scaling and positioning into two steps. The scaled subject specific model can be generated using a single standing/static trial for a subject. The scaled model can then be positioned to the first frame of multiple walking trials.

Figure 1b shows the visualization of muscle activation levels for walking motion. Activation levels were depicted by gradual change in color (Blue: zero activation to Red: high activation). Figure 2 shows the graphical representation of muscle activation patterns for flexor and extensor muscles respectively. Graphs are plotted against gait cycle starting with heel strike; toe off at ~60% and ends (100%) before next heel strike. Muscle activations for 18 trials (6 subjects x 3 trials each) are shown with a different color for each subject (red, green, blue, cyan and magenta). The gray area represents the muscle EMG patterns reported by Perry [4]. The trends of muscle activation patterns correlate well with the EMG data however the levels of activation were different for some muscles.

Ankle extensors (Soleus, FDL, Peroneus) had high activity in terminal stance to generate upward and forward propulsion. Ankle dorsi-flexors (Tibialis Anterior, EDL, EHL) were active at heel strike for eccentric control of plantar-flexion and during swing phase to flex the foot for clearance. Knee extensors (Quads: 3 Vastus muscle shown) were active during initial contact for knee extension and in terminal swing to stiffen knee for weight acceptance in next heel strike.

CONCLUSIONS

It has been shown that musculoskeletal (M-S) modeling based on rigid body dynamics can be implemented by using the commercial software Abaqus for solving inverse dynamics and Isight for process automation and optimization. The Isight workflow for M-S modeling was demonstrated to be robust and repeatable for multiple trials of multiple subjects. The scaling-positioning method to generate subject-specific models was shown to have low intra-subject variability. An alternate two step scaling-positioning method was introduced to eliminate intra-subject variability if standing (static) trial data is available. Model outcomes were validated against EMG data available in [4] and were found to reproduce trends for most muscles. The model outcomes for multiple trials were similar for multiple subjects indicating that the modeling workflow can be used for group comparison studies. Since inverse dynamics is performed using Abaqus more realistic models of joints, ligaments and tissues can be easily added to the model which is subject of ongoing research.

ACKNOWLEDGEMENTS

The authors would like to thank all the subject participants and the motion lab director Dr. Susan D'Andrea for their time and effort for data collection.

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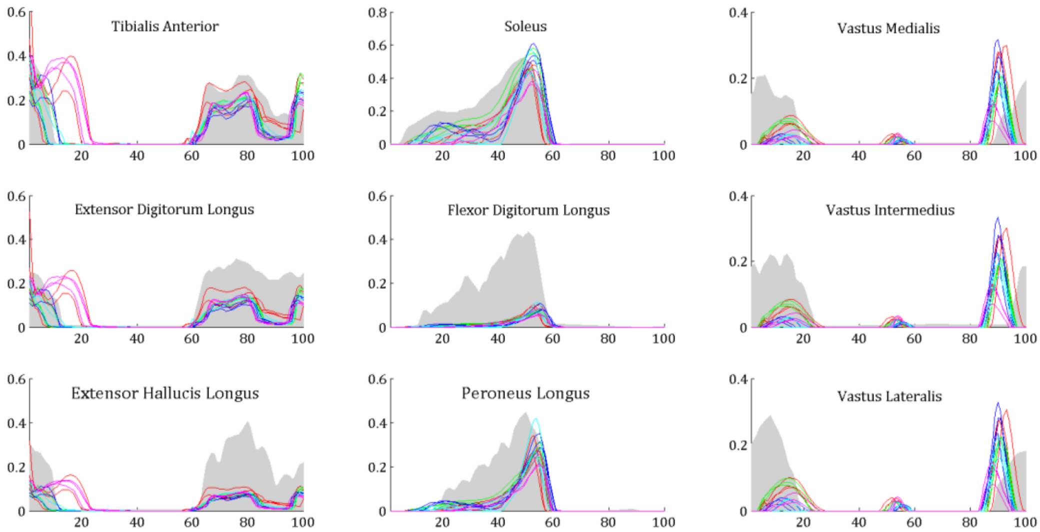

Figure 2: Muscle activation during gait cycle for ankle dorsi-flexors (Tibialis Anterior, EDL and EHL), ankle plantar-flexors (Soleus, FDL, Peroneus Longus) and Knee extensors (Vastus Medialis, Intermedius and Lateralis)