Human Factors Simulation Using Demographically Tuned Biomechanical Models

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We have developed a set of tools based on the OpenSim simulation framework that allows for input of anthropometry, muscle geometry, and measured strength capability to generate demographically tuned models from a core generic musculoskeletal model. The strength tuning capability exploits an algorithm that adaptively tunes muscle parameters in generic Hill-type muscle models to generate performance data consistent with ergonomic subject studies of specific demographic populations (e.g. elderly populations). Following the tuning of the generic model to generate a demographic-specific model, human performance in a variety of scenarios can then be analyzed. Currently, the model is in a prototype phase and has been applied to scenarios modeling elderly passengers interacting with airplane interior features including overhead bins and lavatories. The next phase of development will include manufacturing scenarios with input based on motion capture and worker demographics, including strength measurements.

Introduction

Biomechanical simulation has become increasingly important to the clinical biomedical community in areas like orthopedic surgical planning (Arnold and Delp 2005, Arnold et al. 2006), rehabilitation, sports medicine, and biomedical device analysis (Thompson et al. 2012). Additionally, there is an emerging need for high-fidelity biomechanical simulations in industrial domains like human factors engineering (Rasmussen et al. 2012). However, musculoskeletal models used for biomechanical simulations are either generic models representing an ideal or nominal subject (e.g. 50th percentile 25 year old male), or hand tuned models representing a specific subject (e.g. child with cerebral palsy). Our approach involves autonomously updating musculoskeletal models with subject or demographically tuned strength parameters. The input data required for our approach are isometric strength data measured in standard ergonomic experiments. This facilitates the fast and automatic tuning of musculoskeletal models for individuals or demographic cohorts.

Our tuning approach begins with a generic musculoskeletal model. We have developed a full body model, comprised of 40 degrees of freedom and over 200 musculotendon units, based on combining state of the art anatomical subsystem models acquired from other work.

We then tuned the generic model to elderly male and female demographic groups. The application of interest for employing these elderly demographic models was interaction with airline cabin interiors. The use of demographically-specific musculoskeletal computer models in evaluating the ergonomic effect of various design features for airline cabins provides an opportunity to perform design tradeoffs and optimizations related to usability for target demographic groups (see Figure 1). The fidelity of physics-based biomechanical models provides far more detailed information than traditional simulation approaches involving kinematic manikins. For example, our model exposes over 500 musculoskeletal state variables at each simulation time step with thousands of other derived variables computed as well.

Methods

Musculoskeletal simulation and control

Musculoskeletal dynamics can by modeled by an active state Hill-type musculotendon model coupled with a multibody inertial model of the musculoskeletal system. The state equation for the musculoskeletal plant can be expressed as,

$$(\dot{\boldsymbol{a}} \quad \dot{\boldsymbol{l}}_M \quad \dot{\boldsymbol{q}} \quad \dot{\boldsymbol{v}})^T = \boldsymbol{F}(\boldsymbol{a}, \boldsymbol{l}_M, \boldsymbol{q}, \boldsymbol{v}, \boldsymbol{u}), \qquad (1)$$

The states include the r muscle activations, $\boldsymbol{a}$, and muscle fiber lengths, $\boldsymbol{l}_M$, the n generalized coordinates (joint angles), $\boldsymbol{q}$, and generalized velocities, $\boldsymbol{v}$. The muscle excitations, $\boldsymbol{u}$, form the control input to the musculoskeletal plant. A muscle controller takes a reference motion command, $\boldsymbol{q_d}$, as well as measurements of the musculoskeletal states and generates control inputs to track the reference command.

OpenSim (Delp et al. 2007) was used in this work as the musculoskeletal simulation engine and the computed muscle control algorithm (Thelen et al. 2003, Thelen and Anderson 2006) incorporated within OpenSim was used as the muscle controller.

Generic musculoskeletal model

The complete model used is a combination of the lower body Gait2392 model provided with OpenSim and an upper limb model based on Holzbaur et al. 2005. This upper limb model employs constraints between the glenohumeral, scapulothoracic, sternoclavicular, and acromioclavicular motion of the shoulder (De Sapio et al. 2006). The first step to merging the two models was to use the OpenSim scaling tool to normalize both models to a target basis of height and weight. For the male model this meant scaling the Gait2392 height and weight by .96 and 1.027 respectively, the upper

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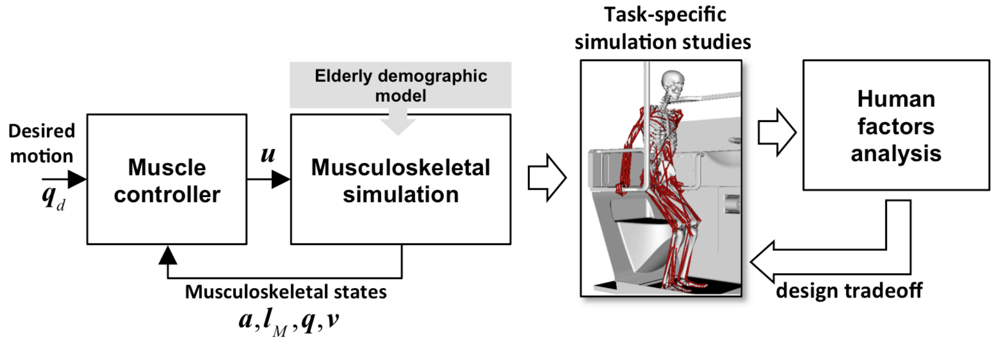

Figure 1: Flow diagram showing a desired motion input associated with performing a specific task and a muscle feedback controller that generates muscle excitations necessary to track the motion. The demographic-specific musculoskeletal simulation outputs state variables and other derived biomechanical variables relevant to high fidelity human factors analysis. This facilitates design tradeoffs that improve human usability.

body model by height and weight .977 and 1.029 respectively. The female height and weight was scaled by .87 and .83 for the Gait2392 and the upper body model was scaled to .887 and .883 respectively.

The original upper body model only contained the right side of the body; therefore the left side was constructed by mirroring the right side. Wrapping surfaces and constraint function splines required manual modification. The actual combination of the models is a straightforward procedure. The "ground" body of the upper body model corresponds to the "torso" in the Gait2392.

Connecting the models consisted of creating a thorax body to which the upper body, starting at the clavicles, was attached and welding the new body to the torso of the Gait2392 at the appropriate position. Anything attached above the torso in the Gait2392 model was eliminated and all the constraint sets, force sets, and marker sets of the upper body model were appended without conflict.

The resulting model consists of approximately 40 degrees of freedom with 200 muscles. In simulation this results in over 500 biomechanical states and thousands of derived variables computed at each time step.

Tuning the generic model to demographic data

We will provide a cursory overview of our strength tuning procedure here. A more detailed exposition of this approach will be presented in a future paper.

The generic musculoskeletal model described in the previous section was tuned using kinetic data from various isometric exercises involving human subjects (Smith et al. 2000). For each exercise, the model is posed in simulation as specified by the particular exercise (see Figure 2). The degrees of freedom of the model are restricted to the joints directly applicable to the exercise (e.g. knee joint in the exercise of Figure 2).

In the actual execution of the exercise by the human subject, the subject exerts the largest force they are capable of while being physically restrained in the isometric pose. However, in the simulation of the exercise, instead of restraining the model and measuring the simulated forces produced, our approach was to use the computed muscle control (CMC) algorithm (Thelen et al. 2003, Thelen and Anderson 2006) incorporated within the OpenSim simulator. The CMC controller is commanded to maintain the model at the isometric test position using neural excitations to the muscles as control inputs. An external force, opposite in direction to the force generated in the actual exercise by the subject, is applied to the model at the test position. In the simulated exercise, the magnitude of the external force starts at zero and linearly increases to the full desired magnitude. The full magnitude of the force is maintained for several simulation cycles to allow the model to stabilize against the full force. If at the end of the simulation the model has not maintained the desired position (isometric stability), the maximum isometric force limits of all the muscles are raised and the process is repeated until the threshold of isometric stability is reached. Conversely, if the model is able to maintain isometric stability the maximum isometric force limits are lowered until the threshold of isometric stability is reached.

At this point, the muscles relevant to the exercise are identified by their activation levels at the end of the simulation. The forces produced by the relevant muscles are recorded. This process is repeated across all the exercises. Once all the exercises have been processed, the forces produced by the relevant muscles are collected. If a muscle is utilized by multiple exercises, the largest force reported is used. The force limits of the muscles in the model are set accordingly (see Figure 2).

Use case simulations

The demographically tuned musculoskeletal model was employed in various use case simulations involving interaction with Boeing 777 economy class cabin features. Two of these simulations are presented here.

Overhead bin closing:

The case of closing an overhead bin was simulated. An inverse kinematics solver was used to generate joint space arm trajectories given the known Cartesian trajectory of the overhead bin mechanism. The CMC controller was used to track these joint space trajectories in closed loop by generating

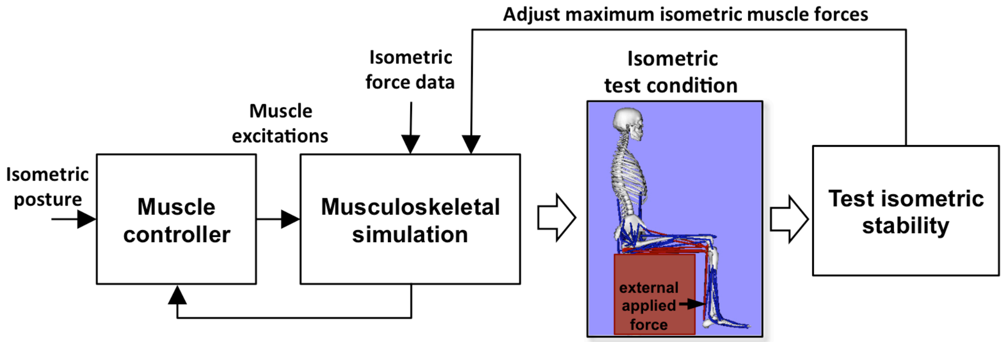

Figure 2: Flow diagram showing the muscle tuning process. The muscle controller (CMC) is commanded to maintain the model at the isometric test position using neural excitations to the muscles. An external force is applied to the model at the test position and maintained. Depending on whether the model is able to maintain isometric stability the maximum isometric forces of all the muscles are raised or lowered and the process is repeated. Activated muscles are shown in red.

muscles excitations that produced joint torques consistent with the tracking dynamics. Different bin closing forces were applied as external forces to the hands. These external closing forces were effectively treated as disturbance forces by the CMC feedback controller while tracking the joint space trajectories. The OpenSim simulator employs an internal multibody dynamics engine (Sherman et al. 2011) to simulate the inertial and gravitational forces acting on the human model.

Lavatory egress:

Lavatory egress was also simulated. Joint space postures were created for a number of stances that utilized horizontal support bars for egress. The assumption made in the simulation is that at all times only the hands and feet interact with the environment and that the movement is slow enough that inertia is a minimal factor. Furthermore the current implementation requires the pelvis to remain stationary within the global reference, however, a moving pelvis can be simulated by transforming the environment by the inverse of the desired pelvic movement. At each time step, the pose is configured by the desired joint angles. A C++ routine that calls the OpenSim API was written that computes the center of mass of the model, as well as the positions of the hands and feet. Forces applied to the hands and feet are calculated such that the sum of the forces equilibrates the force of gravity acting on the body, and that the moment around the center of mass is zero. These forces approximate the expected forces acting on the hands and feet for each time step of the egress sequence. The CMC controller was used to calculate muscle excitation inputs that generated joint torques consistent with the desired postures, in the presence of the external forces.

Results

For bin closing we were interested in the estimated forces generated by the latissimus dorsi muscles during bin closing (Figure 3) among other variables. The latissimus dorsi generates extension, adduction, and internal rotation of the shoulder joint.

The simulation was conducted for moderate and high bin closing forces. Figures 4 and 5 display the simulation results.

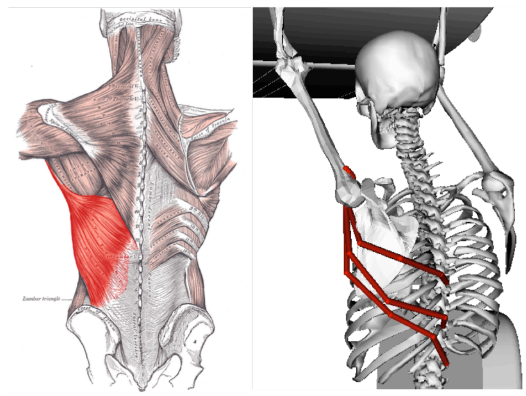

Figure 3: Anatomical depiction (left) of the latissimus dorsi muscles and simulation depiction (right).

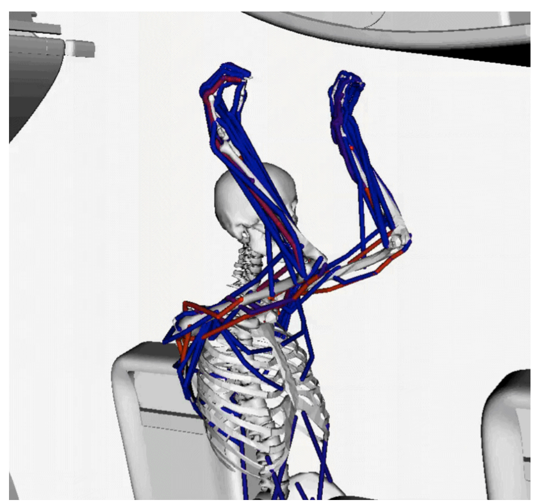

Figure 4: Simulation of bin closing (bin not animated) showing activated muscles (red) at a time step of the simulation.

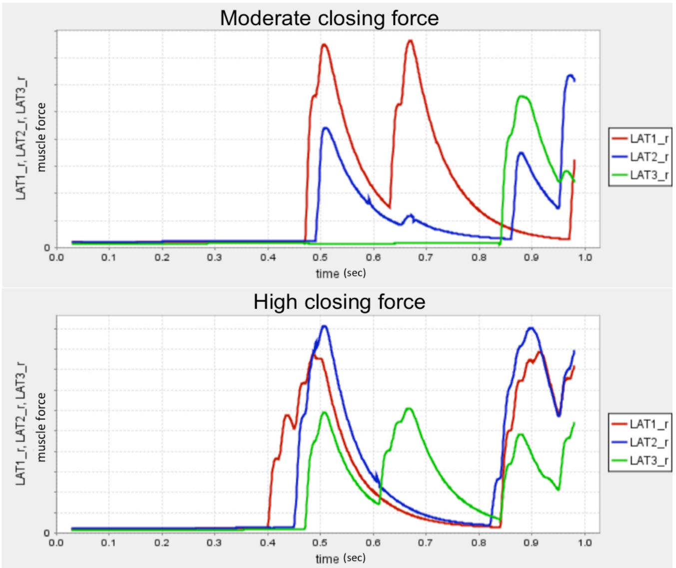

Figure 5: Time history of muscles forces generated by latissimus dorsi muscles during bin closing (force scale intentionally omitted). CMC was used to track bin closing motion with moderate and high closing forces.

For lavatory egress we were interested in the estimated forces generated by the erector spinae, and sartorius muscles during egress stances (Figures 6 and 7). The erector spinae traverse the vertebral column and flex the spine. The sartorius muscle extends from the iliac spine and descends to the knee.

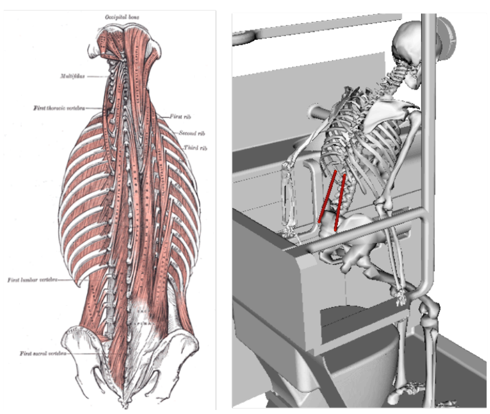

Figure 6: Anatomical depiction (left) of the erector spinae muscles and simulation depiction (right).

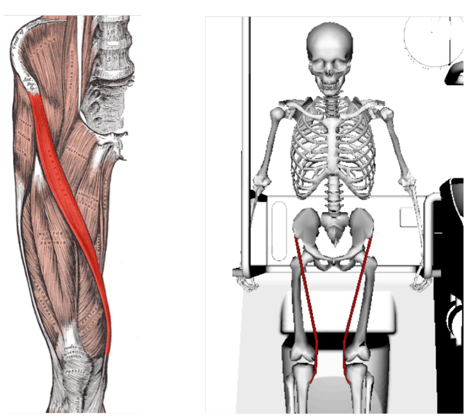

Figure 7: Anatomical depiction (left) of the sartorius muscle and simulation depiction (right).

The simulation was conducted for different egress postures and different horizontal support bar heights. Figures 8 through 10 displays the results of these simulations.

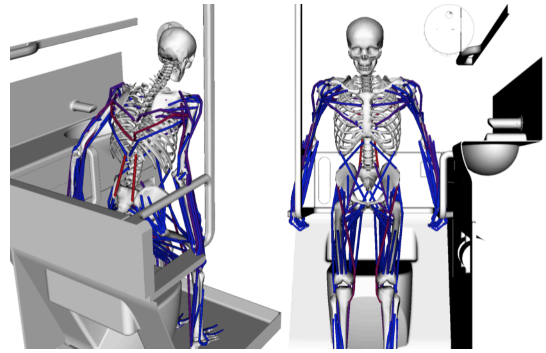

Figure 8: Simulation of lavatory egress showing activated muscles (red) at a time step of the simulation.

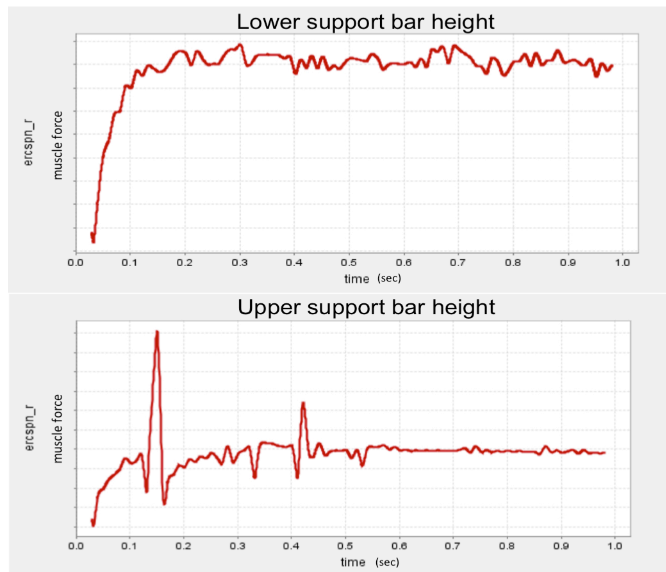

Figure 9: Time history of muscles forces (force scale intentionally omitted) generated by the lower erector spinae muscles during lavatory egress stance.

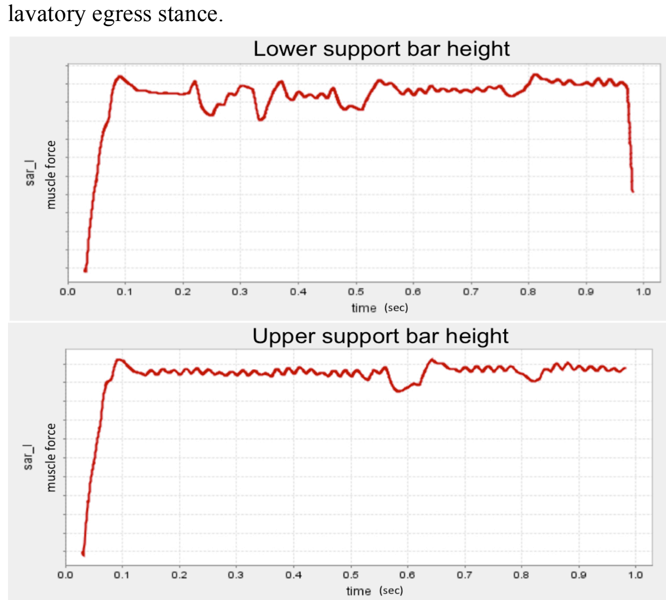

Figure 10: Time history of muscles forces (force scale intentionally omitted) generated by sartorius muscle during lavatory egress stance.

Discussion

The results presented in the previous section are intended to illustrate the utility of musculoskeletal models for the evaluation of cabin interior features from a human factors perspective. Through the use of demographically tuned musculoskeletal models in task specific physics-based simulations we are able to provide next generation human factors capabilities that provide detailed quantitative predictions concerning musculoskeletal physiology.

We characterized the closing of an overhead bin using a model tuned to the strength characteristics of a 50^{th} percentile 75 year old male. We simulated a passenger with these characteristics closing an overhead bin with specific kinematics under a range of closing forces. Subsequently we were able to examine quantitative results of the simulation related to thousands of musculoskeletal variables. As one example we displayed the predicted evolution of muscle forces in the latissimus dorsi muscles given maximum bin closing forces. The bin closing forces and the muscle force scales haven been omitted from the figures as this is proprietary to Boeing.

Similarly, we characterized lavatory egress using a model tuned to the strength characteristics of a 50^{th} percentile 75 year old male. We simulated a passenger with these characteristics getting up from a lavatory while using horizontal support bars, simulated over a range of heights, for assistance. We displayed the predicted evolution of muscle forces in the lower erector spinae, and sartorius muscles at different support bar heights.

Conclusion

Both of the use case simulations discussed in the previous section illustrate specific quantitative analyses that can be used to perform design tradeoffs related to overhead bin and lavatory design for elderly passengers. A formal analysis and tradeoff would involve looking at additional musculoskeletal variables (muscles activations and forces, joint moments, joint reaction forces, etc.) and design variables (bin kinematics, closing forces, lavatory configuration, etc.).

We have developed a framework, described in Figure 1, which allows the autonomous generation of demographic-specific strength parameters for a musculoskeletal model based on data from isometric strength tests (Figure 2). The framework allows the specification of desired motion input associated with performing a specific task. A muscle feedback controller then generates muscle excitations necessary to track the motion. The demographic-specific musculoskeletal simulation outputs state variables and other derived biomechanical variables relevant to high fidelity human factors analysis, that facilitate design tradeoffs.

We are working on new aspects to the work presented here. With regard to the muscle feedback controller we have developed and tested a goal-oriented version of the computed muscle controller that takes high level motion commands (e.g. “move the right hand to location 1 and the left hand to location 2”) as input rather than a full joint space description of the motion (De Sapio 2014). This will allow for much easier specification of desired motion by the user (human factors engineer) since the entire motion does not need to be specified, but rather, only goal relevant components.

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