MUSCLES SLOW SIT-TO-STAND MOVEMENT IN PREDICTIVE SIMULATION

Valerie Norman-Gerum and John McPhee

Systems Design Engineering, University of Waterloo, Canada
Email: normangerum@uwaterloo.ca, Web: uwaterloo.ca/motion-research-group

INTRODUCTION
The purpose of this study is to predict a sit-to-stand (STS) motion imitating that of a healthy human. Garner was first to predict rising of a musculoskeletal model, in 1992 \cite{1}. The current study builds on the recommendations of Garner, to include more uniarticular muscles when modelling STS, and extends a torque-driven model \cite{2} to incorporate muscle units in the STS prediction problem. By including muscles in this new biomechanical model and muscular effort in the new optimal control routine, we are the first to predict STS from a musculoskeletal model with results compared to normative STS motion patterns and events. In predicting healthy STS, this study makes a step toward predicting pathological STS, and then to predicting the results of intervention to inform medical design and planning.

METHODS
Predicting a human motion requires a biomechanical model and theory of how the motion is realized. As STS is the result of coordinated contraction of skeletal muscle, incorporating muscular contributions in the motion prediction problem is integral to solving it. Therefore, the three-link, three-degree-of-freedom, deformable buttocks, sagittal plane biomechanical model in the previous study \cite{2} was augmented with the iliopsoas, rectus femoris, vasti, gluteus maximus, hamstrings, tibialis anterior, gastrocnemius, soleus, flexor digitorum longus, and tibialis posterior muscles, as seen in Figure 1.

The musculoskeletal model in this study was built on the muscle coordinate modelling and scaling work of White et al. \cite{4}, the muscle geometry modelling of Carhart et al. \cite{5}, and the patellar pulley model of Brand et al. \cite{6}. It includes a three-dimensional kinematic model of the patella and models of cylindrical anatomical wrapping constraints for the iliopsoas, rectus femoris, vasti, and gastrocnemius muscles \cite{7}. The musculoskeletal model was motivated by studies of human anatomy and physiology to provide reliable muscle moment arms and muscle lengths for the natural range of sagittal plane joint motions.

The motion prediction problem was divided into two loops. In an inner loop problem (within the “optimize motion paths” block of Figure 2), individual muscle contributions to a candidate STS motion were calculated by solving the static optimization problem for the time-varying muscle forces using fmincon in MATLAB \cite{8}. This problem minimized the sum of squared muscle stresses (eq 1) to resolve muscle indeterminacy.

\[
\min \int ||F^TF - Q||^2 + \rho^2 \sum_{i=1}^{10} \left( \frac{F_i}{PCSA_i} \right)^2 \, dt
\]  

(1)

where the first term penalizes static inconsistency, the second, muscle stress, term is weighted by \( \rho = 10^{-3} \) \cite{9}, where \( F \) is the force exerted by the muscle, and \( PCSA \) is the physiological cross sectional area of the muscle.

This local optimization problem is seeded with muscle forces determined from the seed motion path (within the “find seed of muscle forces” block of Figure 2), considering an alternate form of (eq 1) where the first term is instead expressed as an equality constraint.

In an outer loop problem, candidate motions were optimized to minimize the sum of squared muscle stresses, squared joint torques, and physical infeasibilities, including slipping and falling. The predicted STS was then compared to \cite{2} and to normative STS \cite{10, 11}.

Fig 1: A schematic of the new biomechanical model, created in MapleSim \cite{3}.
RESULTS AND DISCUSSION
The optimal motion paths and corresponding ground reaction forces were used to determine the beginning and end of the predicted STS [10]. The resulting motion is shown in Figure 3. From sitting, the model flexed the HAT (head, arms, and torso), the buttocks lifted from the chair, and the ankles dorsiflexed and then returned to a neutral posture while the knees and hips extended to standing, as would be expected in healthy STS [11].

The final event of STS, “standing on,” was predicted to occur after 2.00s, approximately 0.75 s slower than predicted by the previous model [1], but 0.12 s quicker than what is reported from experiments [10]. However, as seen in Figure 4, all other STS events from this prediction occur within one standard deviation of the norm for healthy STS, which was not the case for the previous, torque-driven, model.

CONCLUSIONS
This study has predicted STS using a three-link musculoskeletal model and a cost function that includes muscular effort. Including muscles in the STS prediction has resulted in slower and more normative timing. However, the static optimization routine that solves for muscle forces has increased computation time drastically, from finding a final solution within hours using the torque-driven model to days using the musculoskeletal model. Nevertheless, muscular contributions have proven influential to predicting realistic STS, and therefore, more efficient strategies of including these muscles and resolving their contributions in a motion prediction routine should be investigated next.

REFERENCES
3. Waterloo Maple, MapleSim, Waterloo, Canada, 2016.
8. The MathWorks, MATLAB, Massachusetts, United States, 2015.

ACKNOWLEDGEMENTS
Supported by the Natural Sciences and Engineering Research Council of Canada and the Canada Research Chairs program.