USING SUBJECT-SPECIFIC STRENGTH COEFFICIENTS TO SCALE MAXIMUM ISOMETRIC FORCES FOR MUSCULOSKELETAL SIMULATION

Hoon Kim[1,2] and Kristof Kipp[3]

Department of Sports Medicine, Soonchunhyang University, Asan, South Korea[1]
Department of Software Convergence, Soonchunhyang University, Asan, South Korea[2]
Department of Physical Therapy, Marquette University, Milwaukee, Wisconsin, USA[3]

The purpose of this study was to develop a novel scaling method for use in musculoskeletal simulations. Four college athletes performed typical dynamic movement and isometric strength tasks, while we captured motion capture, ground reaction force, and muscle activation data. Data from the strength task were used to determine subject-specific estimates of maximum isometric muscle force. Our method showed that subject-specific multipliers ranged from 2.32 to 3.37, and decreased normalized root mean squared error between simulated and EMG-measured muscle activation by 52-90% compared to standard scaling. Although the scaling method worked for only 4/10 athletes, it may provide more realistic simulation results (e.g., muscle activations) than current methods and improve the use of musculoskeletal simulations in the field of sports biomechanics.

KEYWORDS: musculoskeletal simulation, muscle force, isometric squat, OpenSim

INTRODUCTION: Musculoskeletal simulations are commonly used to understand athletic movements because of their ability to comprehensively investigate muscle and joint functions (e.g., muscle forces or joint contact forces) without invasive measurements.
Creating a subject-specific model is key to obtaining realistic outputs and values for use by sports biomechanists. Typically, generic scaling of model parameters is the first step in musculoskeletal simulation. This involves adjusting model parameters, such as body segment lengths and muscle geometry. However, generic scaling is often unable to adequately scale maximum isometric muscle forces (MIMF), which vary widely among individuals and between muscle groups. Inappropriately scaled MIMF may result in unrealistic estimations of muscle activations and forces. For example, musculoskeletal simulations with generic scaling of MIMF often generate saturated muscle activation (i.e., 100% activation) of vastus lateralis and biceps femoris muscles during a squatting task (Catelli et al. 2019). This saturation occurs even though squatting with only body weight is a low-demanded motion compared to many other athletic tasks. Consequently, unrealistic estimation of, e.g., muscle forces, due to inappropriately scaled MIMF may result in incorrect results and ultimately hinder one's ability of using musculoskeletal simulation for making meaningful conclusions.
To more realistically scale MIMF, subject-specific parameters that can be used to adequately scale MIMF from a generic model are needed. Previous studies often scale MIMF by arbitrary constants (e.g., 2 or 3). Handsfield et al. (2014) introduced regression equations that use a person's height and mass to calculate muscle volumes, which can then be used to determine these constants or "strength coefficients". Although models with scaled strength coefficients can produce experimentally observed kinematics and kinetics with sufficiently small residual forces and moments, the arbitrariness of the scaling methods may not be appropriate for use with individual athletes during tasks where high forces are produced.
The purpose of this study was to test a novel method for determining subject-specific strength coefficients to scale MIMF for use in musculoskeletal simulations.

METHODS: Ten National Collegiate Athletics Association Division I female soccer athletes (age: 18.8 ± 0.7, years, mass: 66.9 ± 6.9 kg, height: 1.75 ± 0.05 m) participated in this study.

This study was approved by the University's Institutional Review Board and all participants provided a written consent form. We attached 48 skin markers on the upper and lower extremity and 10 electromyography (EMG) sensors on 10 lower extremity muscles (soleus, gastrocnemius, tibialis anterior, vastus lateralis, vastus medialis, rectus femoris, biceps femoris, semimembranosus, gluteus maximus, and gluteus medius). For this study, we used activations only from soleus, gastrocnemius, vastus lateralis, vastus medialis, biceps femoris, and gluteus maximus.

Participants performed a static standing trial, back squats and deadlifts with 40, 60, and 80% of body weight (BW), isometric squat, isometric mid-thigh pull, isometric calf raise, and maximum repeated hopping. During these tasks, 3D position of reflective markers, ground reaction force (GRF), and muscle activations were recorded by 14 motion capture cameras (100 Hz), 4 force plates (1000 Hz, 2 on ground and 2 on an isometric rack), and 10 EMG sensors (1000 Hz), respectively. Marker and GRF data were filtered with a fourth-order low-pass Butterworth filter at a cut-off frequency of 12 Hz. EMG data were filtered with a fourth-order band-pass Butterworth filter at a cut-off frequency of 20-450 Hz and a low-pass Butterworth filter at a cut-off frequency of 15 Hz.

For each task (e.g., back squats etc.), the maximum EMG amplitude of each muscle was extracted. The overall peak EMG from across all tasks was used to normalize the EMG amplitude of the matching muscle during the isometric squat. These normalized EMG data represent the experimentally observed muscle activation values, which were then compared against values obtained from musculoskeletal simulations with two different scaling approaches. As a proof-of-concept of the proposed scaling method, only data from the isometric squat was used. In addition, two scaling methods below scale all muscles to the same extent using a subject-specific strength coefficient.

For the first approach (***Generic scaling***), a standard musculoskeletal model was scaled with generic parameters (Catelli et al. 2019, Delp et al. 2007). The generic parameters were determined based on data obtained from a static trial. A residual reduction algorithm (RRA) was used to maintain kinematics and kinetics consistency during the isometric squat. Only data from subjects that met the recommended threshold values for the RRA (Hicks et al. 2015) were used for further analysis (n = 4). Predicted muscle activation values during the isometric squat were determined with static optimization and compared against the experimentally observed EMG (Figure 1).

For the second approach (***MIMF Scaling***), the same standard musculoskeletal model was scaled but with subject-specific parameters. Specifically, we iterated through static optimization solutions with different subject-specific strength coefficients. For each iteration, the strength coefficients were incremented by multipliers ranging from 1 (essentially solution from ***Generic scaling***) to 5, to determine a subject-specific MIMF that minimized the normalized root mean squared error (nRMSE) of muscle activations compared to experimentally observed muscle activation values during the isometric squat. The increments for the iterations ranged from 0.01 to 0.5 and varied based on a gradient decent algorithm (Figure 1). We equally multiplied MIMF with the The simulated muscle activations from each iteration were compared against the experimentally observed EMG (Figure 1).

RESULTS: To identify the subject-specific strength coefficients, MIMF scaling went through 47 static optimizations iterations (17 in the first, 9 in the second, and 21 in the third iteration). The subject-specific strength coefficients for four subjects ranged from 2.32 to 3.37 (Mean±SD: 2.70 ± 0.48). The nRMSE with Generic scaling ranged from 62.82 to 91.45% (Mean±SD: 76.52 ± 11.76%), the nRMSE with MIMF scaling ranged from 7.53 to 30.36% (Mean±SD: 19.81 ± 10.04%). Consequently, the %-differences between scaling methods ranged from 52% to 90%.

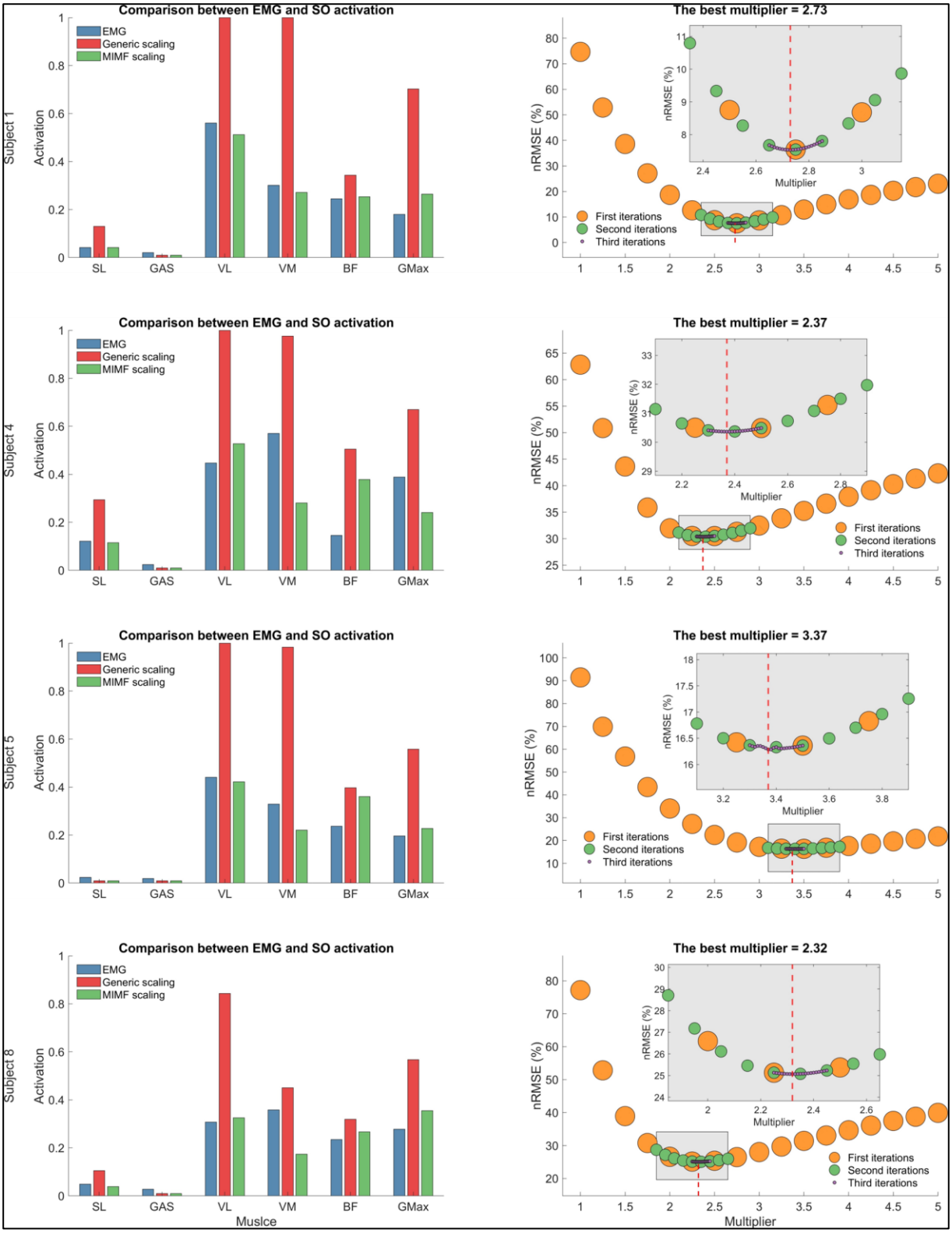

Figure 1: Experimentally observed muscle activations (EMG) and simulated muscle activations from both scaling methods (Generic scaling & MIMF scaling) for four subjects (left column). nRMSE between experimentally observed and simulated muscle activations across static optimization iterations with different strength coefficients for four subjects (right column). Note: Strength coefficient of 1 represents original muscle (i.e., generic) scaling results. SL = soleus, GAS = gastrocnemius, VL = vastus lateralis, VM = vastus medialis, BF = biceps femoris, and GMax = gluteus maximus.

DISCUSSION: The purpose of this study was to test a novel method for determining subject-specific strength coefficients to scale MIMF for use in musculoskeletal simulations. The strength coefficients obtained from our scaling method produced lower nRMSE values than those obtained from a generic scaling method. Specifically, the strength coefficients ranged from 2.32 to 3.37, and produced simulated muscle activations that exhibited 52% to 90% lower errors than generic strength coefficients. These results indicate that using generic or arbitrarily scaled strength coefficients (e.g., 2 or 3) may not be appropriate for use in musculoskeletal simulations in the field of sports biomechanics.

Without subject-specific scaling of MIMF, the simulated activations of the quadriceps muscles during unloaded back squats were almost 100% in all subjects, which indicates that the muscle force in the generic model is not enough to generate the isometric squat in simulation and should need a residual moment in the knee joint. In addition, this indicates that musculoskeletal models without scaling MIMFs can reach incorrect simulation results and conclusions. On the contrary, the simulated results from our scaling method show reasonable activation levels of lower extremity muscles.

The findings of the current study should be interpreted in consideration of several limitations. First, given that volumes of specific muscles may vary between individuals, scaling MIMF should account for subject-specific hypertrophy of different muscle groups. For example, cyclists are likely to exhibit disproportionally greater knee extensor muscle volumes compared to other muscle groups. Second, we only used isometric squat data for scaling MIMF. Validation of scaling MIMF should be additionally conducted using other motions such as back squats, deadlifts, and/or walking. Third, we selectively used EMG data from specific muscles (e.g., SL, GAS, VL, VM, BF, GMax) because we assumed that the isometric squat predominantly requires activations in lower extremity extensor muscles. Adding more muscles that function as antagonists may enhance our scaling method. Fourth, data from six subjects had to be excluded because the residual values during the RRA were higher than recommended. However, four subjects may be sufficient to show the feasibility for use of our method for sports biomechanists.

CONCLUSION: Using subject-specific strength coefficients markedly decreased nRMSE between experimental and simulated muscle activations. The scaling method presented in this paper may provide more realistic results from musculoskeletal simulations than a generic scaling method, and help researchers furnish coaches and athletes with better recommendations. Because our method worked in only 4/10 subjects due to high residuals, future studies should be conducted to reduce residual errors to apply our method.

REFERENCES

Catelli, D. S., Wesseling, M., Jonkers, I., & Lamontagne, M. (2019). A musculoskeletal model customized for squatting task. *Computer methods in biomechanics and biomedical engineering*, *22*(1), 21-24.

Handsfield, G. G., Meyer, C. H., Hart, J. M., Abel, M. F., & Blemker, S. S. (2014). Relationships of 35 lower limb muscles to height and body mass quantified using MRI. *Journal of biomechanics*, *47*(3), 631-638.

Hicks, J. L., Uchida, T. K., Seth, A., Rajagopal, A., & Delp, S. L. (2015). Is my model good enough? Best practices for verification and validation of musculoskeletal models and simulations of movement. *Journal of biomechanical engineering*, *137*(2), 020905.

Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T., ... & Thelen, D. G. (2007). OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE transactions on biomedical engineering*, *54*(11), 1940-1950.

ACKNOWLEDGEMENTS: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2022-00165979) and BK21 FOUR (Fostering Outstanding Universities for Research) (No. 5199990914048). This work was also supported by the Soonchunhyang University Research Fund.