A DIRECT METHOD FOR STUDYING THE INTERACTION BETWEEN MUSCLE VOLUME, LIMB INERTIAL PROPERTIES AND LOWER LIMB MOVEMENT PERFORMANCE

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INTRODUCTION

Skeletal muscles generate the active forces to move and stabilize the limbs. They are highly adaptable, experiencing large volumetric changes throughout life. Skeletal muscle hypertrophies during maturation and in response to strength training and other increased loading stimuli. Skeletal muscle atrophies in response to reduced loading stimuli (e.g. disuse, space flight) and various neuromuscular diseases. Changes in muscle volume affect the muscle's force producing capability, the muscle's line-of-action as well as the line-of-action of peripheral muscles, and the inertial properties of the limb segments containing the muscle. Further, these changes directly affect limb dynamics in a complex, non-linear manner. Current state-of-the-art musculoskeletal modeling strategies model muscle architecture and limb inertial properties as independent quantities. This limits a researcher's ability to study the affects that muscle-tendon morphologic changes have on limb dynamics. The objective of this project was to develop a method for studying the complex interactions between muscle volume, limb inertial properties and lower extremity dynamics.

METHODS

The methodology developed to achieve the stated objective integrated digital data representing lower limb tissue morphology, computational techniques to simulate muscle volume changes within digital tissue data, computational techniques to calculate limb mass, center of mass location, and moments of inertia based on digital tissue data, and musculoskeletal modeling and movement simulation software. The lower limb digital anatomy data used in this study were obtained from a prior study involving the National Library of Medicine's Visual Human Male (VHM) (Barr and Hawkins, 2000). Muscle volume changes were simulated within this data set using algorithms previously developed in our laboratory (Hawkins and Barr, in press). Numerical methods were developed to calculate limb mass, moments of inertia, and center of mass locations. These methods were validated by applying them to common geometric shapes with known inertial quantities.

The above methods allow muscle volume changes to be simulated and new limb inertial properties determined. This approach provides a method for creating a consistent set of data (muscle volume and limb inertial properties) that can be utilized in Software for Interactive Musculoskeletal Modeling (SIMM, Motion Analysis Corporation) to study a variety of musculoskeletal modeling and movement performance issues. The utility of this approach was demonstrated by using it to investigate two specific issues (1) the interactions between muscle volume, limb inertial properties, and movement dynamics, and (2) the implications of using simple regression equations to estimate limb inertial properties in movement simulations. Two lower limb movements were simulated using SIMM, (1) maximally flexing the hip while standing and maintaining a straight leg and (2) maximally flexing the knee while standing and maintaining a neutral hip angle. The movements were purposely chosen to be one joint, unidirectional movements involving maximal effort. This eliminated the need for complex neural control strategies. Limb inertial parameters were defined in these simulations using simple regression models or the methods described above.

RESULTS AND DISCUSSION

There were no errors associated with the numerical method calculations of mass, center of mass and moments of inertia when applied to bodies with known parameters. This provided confidence that the numerical methods could be applied to other bodies. Altering muscle volumes in the VHM model had a greater affect on the shank with respect to increasing the moment of inertia and a greater affect on the thigh with respect to altering the center of mass location. Increasing the mass of triceps surae by 40% increased shank mass by 14.3%. Increasing the mass of the quadriceps by 40% increased thigh mass by 9.6%. Increasing the mass of the quadriceps muscles by 40% had the effect of moving the center of mass location distally by 0.4% of the limb length. Increasing the mass of the triceps surae muscles by 40% had the affect of moving the shank center of mass location proximally by 1.1% of segment length.

The above results contributed to an increase in the moment of inertia of the thigh from 2.4% at 10% hypertrophy up to 8.9% at 40% hypertrophy and the shank from 2.9% at 10% hypertrophy up to 12.1% at 40% hypertrophy. Results show that simple regression equation estimates of segment mass, center of mass and moment of inertia may be in error by 15-35%. However, the nature of these errors tends to offset each other in the equations of motion, allowing simple regression estimates to provide reasonable dynamic responses for the movements simulated. Vmax for both the hip and knee increased similarly as the limbs were hypertrophied. Hip flexion Vmax for the morphed quadriceps conditions shows a steady increase up to 5.3% above the original for a 40% increase in quadriceps muscle volume. Knee flexion Vmax for the morphed shank conditions increased steadily to 5.1% above the original.

SUMMARY

A method for studying the complex interactions between muscle volume, limb inertial properties and lower extremity dynamics was developed. While this method demonstrated there were errors in simple regression equation estimates of limb mass, center of mass location and moments of inertia, the errors in each of the quantities tended to offset each allowing the regression equations to provide reasonable estimates of limb dynamics for simple movements.

REFERENCES

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ACKNOWLEDGEMENTS

The authors are grateful to the J.C. Downing Foundation for financially supporting this project and the NLM Visual Human Project for the images of the lower extremity.