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Muscle Contributions to Frontal and Transverse Plane Whole-Body Angular Momentum

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MUSCLE CONTRIBUTIONS TO FRONTAL AND TRANSVERSE PLANE WHOLE-BODY ANGULAR MOMENTUM DURING WALKING

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SUMMARY

A 3D musculoskeletal modeling and simulation analysis was performed to identify the contributions of gravity and individual muscles to frontal and transverse plane whole-body angular momentum during normal walking. The analysis showed that transverse plane angular momentum is low and nearly all muscles make small contributions to it. In contrast, the frontal plane angular momentum was much larger and dominated by a few muscle groups. The vasti, soleus, gastrocnemius, adductor magnus and gravity were the primary contributors to positive angular momentum (i.e., they acted to rotate the body towards the contralateral leg) while the gluteus medius was the primary contributor to negative angular momentum (i.e., it acted to rotate the body towards the ipsilateral leg). These results have important implications for developing locomotor therapies that target specific muscle groups to improve movement stability.

INTRODUCTION

The regulation of whole-body angular momentum is essential to maintaining dynamic balance during human walking. The primary mechanism to regulate angular momentum is muscle force generation, which accelerates the body segments and generates ground reaction forces that alter angular momentum about the body's center-of-mass to restore and maintain dynamic stability. We previously analyzed the contributions of gravity and individual muscles to sagittal plane whole-body angular momentum and found in early stance, the uniarticular hip and knee extensors, biarticular hamstrings and ankle dorsiflexors generated backward angular momentum while the ankle plantar flexors generated forward momentum [1]. In late stance, the plantar flexors were the primary contributors and generated angular momentum in opposite directions. The soleus generated primarily forward angular momentum while the gastrocnemius generated backward momentum. Gravity contributed to the body's angular momentum in early stance and to a lesser extent in late stance, which was counteracted primarily by the plantar flexors. The purpose of this study was to build upon our previous work by analyzing how gravity and individual muscles contribute to frontal and transverse plane whole-body angular momentum. Identifying which muscles are responsible for generating angular momentum has important implications for the diagnosis and treatment of movement disorders.

METHODS

The 3D bipedal musculoskeletal model was developed using SIMM/Dynamics Pipeline (MusculoGraphics, Inc.) and consisted of ten rigid-body segments representing the thorax, pelvis, and right and left legs, with each leg consisting of a thigh, shank, foot and toes. The model had 23 degrees-of-freedom that fully characterized the kinematic motions of the sagittal, frontal and transverse planes during human walking. The model's dynamical equations-of-motion were derived using SD/FAST (PTC). Foot-ground contact was modeled using 31 visco-elastic elements with coulomb friction distributed along the bottom of each foot.

The model was driven by 38 Hill-type musculotendon actuators for each leg that were combined into 17 muscle groups for the analysis (i.e., those muscles with similar anatomical and biomechanical function were combined together). Muscle force-producing properties were governed by passive force-length-velocity, active force-length-velocity and tendon force-length relationships. Muscle activation dynamics were modeled with a nonlinear first-order differential equation [2].

A walking simulation of a complete gait cycle was generated using dynamic optimization that fine-tuned the muscle excitation patterns of each muscle group such that the difference between the simulated and experimentally measured walking data (see below) was minimized.

Experimental Data

Kinematic, ground reaction force and muscle EMG data were collected from 14 healthy adults as they walked for 30 seconds at 1.2 m/s on a split-belt instrumented treadmill (Tecmachine). Bilateral EMG data were recorded from the tibialis anterior, soleus, medial gastrocnemius, vastus medialis, rectus femoris, bicep femoris long head, semimembranosus and gluteus medius using a 16-channel EMG system (Konisburg Instruments). Force, EMG and kinematic data were collected at 2000 Hz, 2000 Hz and 100 Hz, respectively. Force and kinematic data were low-pass filtered at 20 and 6 Hz, respectively. EMG signals were high-pass filtered (40 Hz), demeaned, rectified and low-pass filtered (4 Hz). All data were processed using Visual3D (C-motion, Inc.).

Muscle Contributions to Angular Momentum

To identify how individual muscles and gravity contribute to frontal and transverse plane whole-body angular momentum, we quantified their contributions to the time rate of change of angular momentum over the gait cycle using the following relation:

$$\dot{\bar{H}} = \bar{r} \times \bar{F}_{GRF}$$

where $\dot{\bar{H}}$ is the time rate of change of whole-body angular momentum, $\bar{r}$ is the moment arm vector from each foot's center-of-pressure to the body's center-of-mass, and $\bar{F}_{GRF}$ is each muscle and gravity's contribution to the ground reaction forces determined using a ground reaction force decomposition technique [2]. The $\bar{r} \times \bar{F}_{GRF}$ term represents the external moment generated about the body's center-of-mass by individual muscles and gravity.

RESULTS AND DISCUSSION

The walking simulation emulated well the group-averaged kinematic and ground reaction force data. All joint angles and normalized ground reaction forces were within +/- 2 S.D. of the experimental data with an average absolute difference of 4.5 deg and 3.7% BW, respectively, and therefore the simulation was representative of normal walking mechanics. The transverse plane angular momentum was small compared to the frontal plane, which was consistent with previous studies (e.g., [3]). Nearly all muscles had small contributions to transverse plane angular momentum. In contrast, the frontal plane angular momentum was much larger and dominated by a few muscle groups (Fig. 1). The vasti, soleus, gastrocnemius, adductor magnus and gravity, and to a lesser extent the biarticular hamstrings, were the primary contributors to positive angular momentum (i.e., they acted to rotate the body towards the contralateral leg) while the gluteus medius, and to a lesser extent the tensor fasciae latae, were the primary contributors to negative angular momentum (i.e., they acted to rotate the body towards the ipsilateral leg).

These results were consistent with a recent study showing the vasti, soleus, gastrocnemius and gravity are the primary contributors to the body's lateral acceleration of the center-of-mass during walking, while the gluteus medius is the primary contributor to the body's medial acceleration of the center-of-mass [4]. During normal walking, angular momentum is generated about the body's center-of-mass by movements of the body segments and the interaction of the feet with the ground that generates an external moment on the body. Thus, how a muscle contributes to whole-body angular momentum should be consistent with its contributions to the ground reaction forces and how they accelerate the body's center-of-mass.

In contrast to our previous work showing soleus and gastrocnemius had opposite effects on sagittal plane angular momentum in late stance [1], both muscles worked in synergy to provide positive frontal plane angular momentum. Gravity was also found to generate positive frontal plane angular momentum throughout stance, which was counteracted primarily by the gluteus medius (Fig. 1). Thus, hip adductor activity is critical to counteract the contributions of gravity and other muscles to restore and maintain dynamic stability during walking.

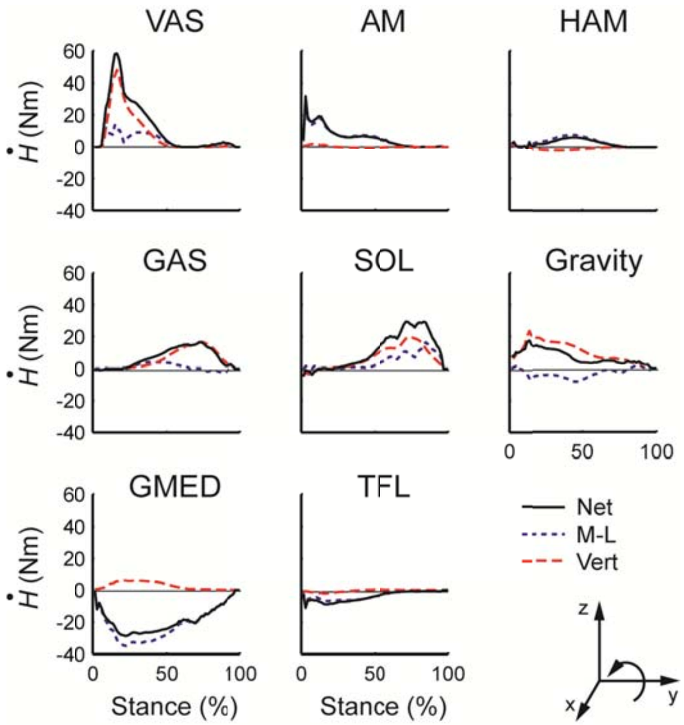

Figure 1: Individual muscle contributions to frontal plane whole-body angular momentum ($\dot{H}$ about the y-axis) for the vasti (VAS), adductor magnus (AM), biarticular hamstrings (HAM), gastrocnemius (GAS), soleus (SOL), gluteus medius (GMED), tensor fasciae latae (TFL) and gravity. Note, the contralateral leg muscles would have opposite contributions during their corresponding stance phase.

CONCLUSIONS

These results highlight the importance of hip adductor activity in maintaining and restoring dynamic stability in the frontal plane during human walking. Thus, locomotor therapies that target these muscle groups may be helpful in improving movement stability.

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