ISB 2013 BRAZIL
XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

CONTRIBUTIONS OF SUPPORT LIMB MUSCLES TO RECOVERY FROM A STUMBLE

Bahar Sharafi and Yasin Dhaher
Rehabilitation Institute of Chicago, Chicago IL, USA
email: bahar.sharafi@northwestern.edu

SUMMARY

We created three-dimensional muscle-actuated forward dynamic simulations of recovery from a stumble. To analyze contributions of individual muscles to the recovery response, we eliminated the recovery-specific muscle excitations from the excitation time history of the corresponding muscle and ran new simulations with the altered excitations for each muscle or groups of muscles. We then quantified the contribution of each muscle by comparing the center of mass (COM) position and joint angles at the end of the recovery step for each simulation with altered excitations with a baseline simulation that tracked experimental kinematics. We found that the cumulative effect of muscle excitations resulting from the trip was to continue to propel the COM forward, while providing support and arresting the forward-directed rotation of the torso. This was accomplished by producing a posteriorly directed reaction moment about the COM of the body and by preventing the knee from buckling. The muscles contributing the most to raising the COM were the rectus femoris followed by the glutei maximus and medius. The muscles contributing the most to arresting the forward rotation of the torso were the biceps femoris followed by the glutei maximus and medius.

INTRODUCTION

Falls resulting from a trip are common among patients suffering from neurological disorders [1, 2]. While it has been shown that successful recovery from a stumble correlates with the ability to arrest the forward rotation of the torso [3, 4], it is not clear how individual muscles or groups of muscles contribute to this task. Additionally, existing experimental studies disagree on whether lower limb strength adequately separates fallers from non-fallers [5, 6].

The purpose of this study was to determine the contribution of support limb muscle activation patterns to recovery from an induced trip. To this end, we created a three-dimensional forward dynamic simulation of an elevating recovery strategy [7] following a trip induced during the early swing phase.

METHODS

Marker trajectories and ground reaction forces and moments were recorded for a single subject (male, healthy, weight 80kg, height 1.73Cm) walking on a treadmill. The foot was obstructed at different points in the swing phase using a previously described setup [8] to induce a forward-directed trip. Bilateral EMG were collected from gluteus Maximus (GMA), gluteus medius (GME), adductor magnus (ADD), biceps femoris (BF), semitendinosus (ST)., rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), gastrocnemius medialis (GM), soleus (SOL), peroneus longus (PL), and tibialis anterior (TA). Additionally, the force acting on the swing foot during the trip was recorded. EMG signals were analyzed to identify the onset and magnitude of recovery-specific muscle responses [7]. A three-dimensional model including 92 muscles [8] was scaled to match subject anthropometry. A typical recovery response consisting of an elevating strategy in response to a trip induced in the early swing phase was selected for simulation. A muscle-actuated simulation was generated using the Computed Muscle Control (CMC) algorithm [9] in OpenSim [10] to track measured kinematics given the experimentally measured external forces. Muscle excitations were constrained based on experimental EMG. Muscle excitations calculated via CMC were then used to actuate a forward dynamic model where the ground reactions were replaced by Hunt-Crossley contact forces [11]. The geometry of the contact model consisted of three spheres placed on the calcaneus of the support foot. Contact parameters where adjusted and initial joint angles and velocities where slightly modified such that the initial contact forces closely matched the experimentally measured ground reaction forces. The experimentally measured trip force was applied to the swing foot as an external force. For each muscle or group of muscles, portions of the excitation identified as recovery-specific where separately eliminated from the excitation time history and the forward dynamics simulation was run from the onset of the trip until just before the heel strike of the ipsilateral foot. The contribution of each muscle or group of muscles was quantified by comparing the COM and joint angles at the end of each of the altered simulations with a baseline simulation that used the muscle excitations obtained from CMC and reproduced the experimentally measured kinematics. This process was repeated for all muscles for which EMG measurements were available.

RESULTS AND DISCUSSION

The baseline simulation closely matched the measured kinematics and ground reaction forces.

The cumulative effect of the recovery-specific response of the major muscles of the support leg is to continue to propel the body COM forward while maintaining the vertical position of the COM and arresting the forward rotation of the torso (Figure 1). The vertical position of the COM is primarily maintained by extending the knee (Figure 1), thereby preventing it from buckling. Limiting the forward rotation of the torso is achieved primarily by extending the support hip and generating a posteriorly directed ground reaction moment about the COM of the body. The RF recovery response provided the greatest contribution to maintaining the vertical position of the COM by extending the knee. The RF was followed by GME and GMA. The uni-articular muscles of the hip contributed to the COM vertical position primarily by extending the knee through intersegmental dynamics (Figure 2). Conversely, the BF lowered the COM by flexing the knee. The BF recovery response provided the greatest contribution to preventing the forward rotation of the torso by extending the support hip followed by the GMA and GME. Conversely, the RF rotated the torso forward by flexing the hip. While GME and ADD are primarily hip ab/adductors, both of these muscles produced significant hip extension moments, thereby contributing to both the maintenance vertical COM position and the arrest of the forward rotation of the torso.

Figure 1: Model pose at the end of the baseline simulation which tracks the experimental kinematics closely (light shade) is super-imposed over the model pose at the end of an altered simulation were the recovery-specific excitations of the major muscles have been eliminated from the excitation time history (darker shade). Buckling of the knee and the lowering of the COM are apparent.

CONCLUSIONS

Previous studies have suggested that the arrest of the forward rotation of the torso is critical to successful recovery from a stumble [3, 4]. Our results suggest that the goal of the recovery response in the context of an elevating strategy is to additionally maintain the vertical position and continue the forward motion of the COM. Our findings are in agreement with a previous study that correlated leg extension strength with successful recovery from induced trips through a regression analysis [5]. However, the role of individual muscles and mechanisms through which they contribute to a successful recovery had not been previously identified. These results will enable us to better analyze unsuccessful recovery responses (and thereby propensity for falls) in the presence neural constraints stemming from motor control disorders and ultimately aid in the design of targeted interventions to improve balance recovery.

ACKNOWLEDGEMENTS

We are grateful to Ajay Seth, Jennifer Hicks, and Camila Shirota. Funding for this work was provided by NINDS grant 5R01NS064084-02, the National Center for Simulation in Rehabilitation Research (NIH grant R24 HD065690), and NIDR grant H133P110013-12.

REFERENCES

1. Morris ME. *Physical Therapy* **86,** 1426-1435, October 2006.
2. Schmid AA and M Rittman. *Topics in stroke rehabilitation* **14,** 46-55, 2007.
3. Grabiner MD, et al. *J.Gerontol.* **48,** M97-M102, 1993.
4. Pavol MJ, et al. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* **56,** M428-M437, 2001.
5. Pijnappels M, et al. *Eur.J.Appl.Physiol.* **102,** 585-592, 2008.
6. Pavol MJ, et al. *J.Am.Geriatr.Soc.* **50,** 256-262, 2002.
7. Eng JJ, et al. *Experimental Brain Research* **102,** 339-349, 1994.
8. Hamner SR, et al. *J.Biomech.* **43,** 2709-2716, 2010.
9. Thelen DG and FC Anderson. *J.Biomech.* **39,** 1107-1115, 2006.
10. Delp SL, et al. *IEEE Trans.Biomed.Eng.* **37,** 757-767, 1990.
11. Hunt K and F Crossley. *J.Appl.Mech.* 1975.

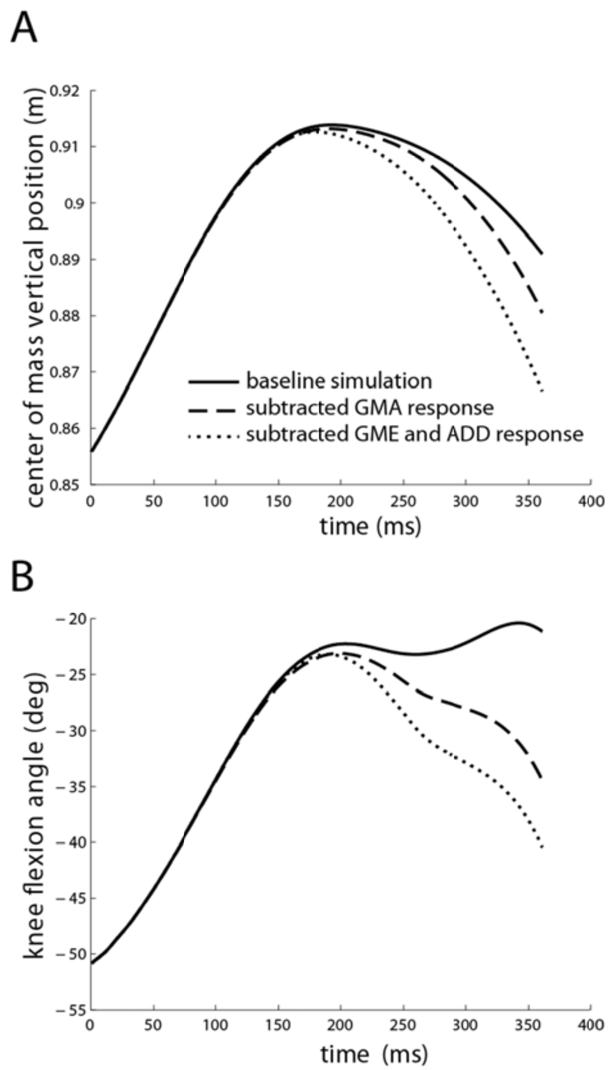

Figure 2: COM vertical trajectories (A) and knee flexion angle (B) are given as a function of time passed from trip onset for the baseline simulation which tracks the experimental kinematics closely (solid line), an altered simulation where the recovery-specific response of the GMA has been eliminated (dashed line), and an altered simulation where the recovery-specific response of the GME and ADD have been eliminated (dotted line). Negative angles denote flexion.