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Effects of aging-related losses in strength on the ability to recover from a backward balance loss

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ABSTRACT

Although muscle weakness is a risk factor for falls, its direct influence on the ability to prevent a fall is largely unknown. This study therefore investigated the effect of aging-related losses in strength on the ability to restore static balance following a recovery step from a backward balance loss. A six-link, sagittal-plane musculoskeletal model with 10 Hill-type musculotendon actuators was developed to simulate the strength characteristics and balance recovery motions of young and older adults. Using this model, feasible regions for balance recovery were mapped for each age group for "slow" and "fast" initial conditions of backward and downward velocity. For both conditions, there was considerable overlap between the feasible regions of young and older adults, with both age groups able to restore static balance from similar initial hip heights. However, the ranges of initial center of mass positions, relative to the rear heel, for which balance could be restored did not extend as far anteriorly or posteriorly for older adults. The feasible region did not extend as far upward, downward, or posteriorly for the "fast" condition, with these differences between conditions being similar in each age group. The results suggest that aging-related losses in strength impair the ability to recover from a backward balance loss only if older adults take a very short or very long recovery step behind the center of mass, even for high velocities at step touchdown. Training of the stepping response might therefore be more effective than strength training in preventing backward falls.

1. Introduction

Falls have large impacts on older adults and society. In 2000 in the United States, 2.6 million adults aged 65 or older received medical treatment for fall-related injuries, at a cost of approximately $19.2 billion (Stevens et al., 2006). Fall-related hip fractures are of particular concern, due to resulting limitations in activities of daily living (Wolinsky et al., 1997) and a 10% increase in mortality rate (Leibson et al., 2002). Impact to the hip is most likely to result from a backward or sideways fall (Smeesters et al., 2001), of which the former is harder to prevent (Hsiao and Robinovitch, 1998). Preventing backward falls by older adults is thus imperative.

A reduced ability to prevent a backward fall may result from aging-related losses in muscle strength. Muscle undergoes multiple changes with advancing age (Campbell et al., 1973; Lexell et al., 1988), such that, by their 70s, older adults typically lose 20–40% of their strength (Doherty, 2003) with accompanying losses of muscle power (Thom et al., 2007). Reductions in muscle strength have been implicated as possible contributors to impairments in preventing a fall (Moreland et al., 2004). In particular, aging-related strength losses may impair the ability to support the body and arrest its motion after a recovery step. Larger lower extremity moments are used during stance after a forward recovery step than during stepping, and older adults show alterations in these moments consistent with compensation for losses in knee strength (Madigan and Lloyd, 2005). Yet, a meta-analysis found no consistent effect of strength training on falls in older adults (Province et al., 1995) and older adults who fell following an induced trip were stronger than non-fallers (Pavol et al., 2002). Thus, the extent to which aging-related strength losses impair the ability to prevent a fall, specifically backward falls, remains unclear.

One approach to resolving this issue is to determine the effects of aging-related strength losses on the feasible region for balance recovery. Pai and Patton (1997) defined this region as the set of initial horizontal positions and velocities of the body center of mass (COM) for which the COM can be brought to rest above the base of support without stepping. Using an inverted pendulum model, they found that small-to-moderate losses in ankle muscle strength did not affect the feasible region. However, this may not apply to balance restoration after a recovery step from a backward balance loss, as the knee flexion and hip descent that are typically present at step touchdown (Pavol and Pai, 2007) were not considered.

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The present study used a modified version of the feasible region for balance recovery to specifically assess the extent to which aging-related losses in muscle strength affect the ability to restore static balance following a recovery step from a backward balance loss. A musculoskeletal model was developed to simulate the strength characteristics and balance recovery motions of young and older adults. Effects of initial horizontal and vertical positions and velocities on the ability to restore balance were then determined by computing and comparing the feasible regions between age groups for selected initial velocities.

2. Methods

2.1. Model formulation

A six-link model was developed to simulate the balance recovery motions of young and older adults in the sagittal plane after touchdown of a backward step (Fig. 1a; supplementary material). Links of the model corresponded to the two feet, rear leg, rear thigh, head–arms–torso, and front thigh-and-leg, connected by hinge joints at the ankles, knee, and hips. Segment lengths and inertial properties were determined from Winter (2005) for an individual with a body height (Bh) of 1.8 m and mass of 75 kg. The rear foot remained stationary, whereas the front foot was constrained to slide along the ground. The coefficient of friction beneath the front foot was a sigmoid function of velocity (van den Bogert et al., 1989), reaching 90% of its maximum of 0.7 at 5 cm/s.

The rear limb of the model was controlled by 10 musculotendon actuators that simulated the major uni- and biarticular extensor and flexor muscle groups across the ankle, knee, and hip (Table 1). Musculoskeletal geometry was derived from Delp (1990). The actuators were Hill-type musculotendon models, with a contractile element (CE) and parallel elastic (PE) element acting through a series elastic (SE) element (Fig. 1b). CE force was

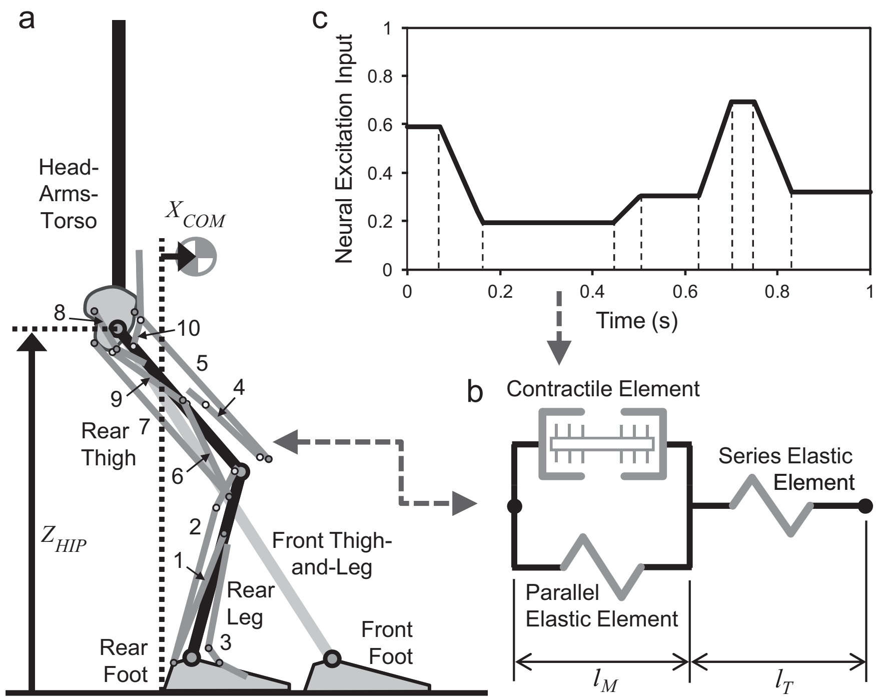

Fig. 1. (a) Six-link, sagittal-plane model used to simulate the restoration of static balance after touchdown of a recovery step from a backward balance loss. The rear foot remained stationary; the front foot slid along the ground; and control was provided by 10 musculotendon actuators acting on the rear limb (Table 1). The initial state was specified by the position of the body center of mass (X_{COM}) anterior to the rear heel, the hip height (Z_{HIP}), and the corresponding velocities. (b) Each musculotendon actuator consisted of a contractile element (CE) and parallel elastic (PE) element acting in series with a series elastic (SE) element. The PE and SE elements were non-linear springs, while the CE force output depended on neural excitation, excitation–activation dynamics, muscle length (l_M), and muscle strain rate. (c) The neural excitation input to the CE ranged from 0 (none) to 1 (maximum) and was parameterized by the start time, magnitude, and stop time of up to five periods of constant excitation, with these periods connected by linear changes in excitation. l_T=tendon length.

Table 1
Musculotendon actuators included in the model.

Actuator*	Component muscles	Joints crossed
1. Soleus	Soleus	Ankle
2. Gastrocnemius	Gastrocnemius lateralis, gastrocnemius medialis	Ankle, knee
3. Dorsiflexors	Tibialis anterior, extensor digitorum longus, extensor hallucis longus	Ankle
4. Vastii	Vastus lateralis, vastus medialis, vastus intermedius	Knee
5. Rectus femoris	Rectus femoris	Knee, hip
6. Biceps femoris	Biceps femoris short head	Knee
7. Hamstrings	Biceps femoris long head, semitendinosus, semimembranosus	Knee, hip
8. Gluteals	Gluteus minimus, gluteus medius, gluteus maximus	Hip
9. Adductor magnus	Adductor magnus	Hip
10. Iliopsoas	Iliacus, psoas major	Hip

* Numbers correspond to actuators shown in Fig. 1a.