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Biomechanical predictors of maximal balance recovery performance amongst community-dwelling older adults

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ABSTRACT

Falls are prevalent in older adults and are predicted by the maximum forward lean magnitude (MRLM) that can be recovered using a single step. The purpose of this study was to determine the relative contribution of selected neuromuscular and biomechanical variables associated with balance recovery to the MRLM. Forward loss of balance was induced by releasing participants ($n = 117$ community-dwelling older adults) from a static forward lean angle. Participants were instructed to attempt to recover balance by taking a single step. A scalable anatomical model consisting of 36 degrees-of-freedom was used to compute kinematics and joint moments from motion capture and force plate data. Isometric muscle strength at the ankle, knee and hip joints was assessed using a dynamometer. A univariate analysis revealed that lower limb strength measures, step recovery kinematics, and stepping limb kinetics accounted for between 8 and 19%, 3 and 59%, and 3 and 61% of the variance in MRLM respectively. When all variables were entered into a stepwise multiple regression analysis, normalised step length, peak hip extension moment, trunk angle at foot contact, and peak hip flexion power during stepping together accounted for 69% of the variance in MRLM. These findings confirm that successful recovery from forward loss of balance is a whole body control task that requires adequate trunk control and generation of adequate lower limb moments and powers to generate a long and rapid step. Training programmes that specifically target these measures may be effective in improving balance recovery performance and thereby contribute to fall prevention amongst older adults.

1. Introduction

Falls in older adults are a major public health concern (Lord, 2007) and occur when an individual experiences loss of balance from which they are subsequently unable to recover. There is convincing evidence that the ability to recover from forward (Carty et al., 2011; Thelen et al., 1997), backward (Hsiao and Robinovitch, 2001) and sideways (Hilliard et al., 2008; Maki et al., 2000) loss of balance is compromised in older adults. The tether release method is commonly used to study recovery from forward loss of balance (Arampatzis et al., 2008; Carty et al., 2011; Karamanidis and Arampatzis, 2007), it has been shown that older compared to younger adults are more likely to adopt a multiple compared to single step recovery strategy when released from a given initial static forward lean angle (Carty et al., 2011; Thelen et al., 1997) and have a smaller maximum initial lean angle from which they can recover with a single step (Thelen et al., 1997). It has further been demonstrated that older multiple compared to single steppers, and those with a low versus high maximum release angle from which they can recover with a single step are more likely to experience a fall in the following 12 months (Carty et al., 2015). It therefore follows that efforts to understand the mechanisms underlying the high incidence of falls in older adults should focus on identifying factors that affect the ability of older adults to recover from loss of balance. Targeted interventions to address those deficits can be subsequently developed and evaluated.

Studies of recovery from forward loss of balance to date have reported muscle weakness and altered step kinematics and kinetics during recovery as factors underlying either age-related declines in balance recovery, or reduced balance recovery performance amongst older adults. For example lower extremity strength of older adults significantly predicted use of a single versus multiple step recovery strategy (Carty et al., 2012a), strength of the triceps surae and quadriceps muscles accounted for between 35% and 55% of the variance in margin of stability between young and older adults (Karamanidis and Arampatzis, 2007) and, ankle dorsiflexion strength explained 30% of the variance on MRLM of older adults (Grabiner et al., 2005). Studies of recovery kinematics have further demonstrated that a single step compared to a multiple step strategy was characterised by the production of an adequately long (Karamanidis et al., 2008; Schillings et al., 2005) and rapid first step (Owings et al., 2001) coupled with a lower amplitude and rate of trunk flexion (Bieryla et al., 2007; Crenshaw et al., 2012). Furthermore, trunk flexion angle at foot contact and step length have been shown to account for 51% of the

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variance in whole body dynamic stability at the time of foot contact of the stepping leg (Carty et al., 2011) and correctly classified 92.3% of falls and recoveries from treadmill induced loss of balance (Grabiner et al., 2012). Peak hip flexion and knee extension joint moments and/or joint powers in the stepping leg during recovery also distinguish between older single and multiple steppers (Carty et al., 2012b) and young and older adults (Madigan, 2006). Graham et al. (2014) also reported differences in the magnitude of hip peak abductor muscle force in the non-stepping limb in older single and multiple steppers. Despite the aforementioned studies no study to date has evaluated a comprehensive range of strength, kinematic and kinetic predictors of balance recovery in older adults using multivariate models.

The purpose of the present study was to identify the biomechanical factors that distinguish between older adults who can recover with a single step from a small and large MRLM. The ability of these variables to predict MRLM was subsequently investigated. Our hypothesis was that task-specific measures of balance recovery would explain additional variance in predicting MRLM compared to measures of isometric lower limb strength previously reported (Grabiner et al., 2005; Karamanidis and Arampatzis, 2007) and that balance recovery measures previously shown to predict successful recovery from a given static lean magnitude (Carty et al., 2012a, 2011) and from a rapid disruption of balance (Crenshaw et al., 2012; Grabiner et al., 2012) would also predict MRLM.

2. Methods

2.1. Participants

One hundred and seventeen community dwelling older adults aged 65 to 80 years (60 men, 57 women; age: 72 ± 4.9 years; height: 1.67 ± 0.09 m, mass: 76.0 ± 13.3 kg) were recruited at random from the local electoral roll. Individuals previously diagnosed with neurological, metabolic, cardio-pulmonary, musculoskeletal and/or uncorrected visual impairment were excluded. Ethics approval was obtained from the Institutional Human Research Ethics Committee and all relevant ethics guidelines including provision of informed consent were followed.

2.2. Experimental protocol

Participants attended the biomechanics laboratory on a single occasion and initially underwent a balance recovery assessment to determine their MRLM and corresponding measures of recovery kinematics (step length, step time, trunk angle and angular velocity at toe off and foot contact) and kinetics (peak joint moments and powers in both the stepping limb and stance limb). Ankle, knee and hip strength of the stepping lower limb was subsequently assessed on a dynamometer.

2.3. Balance recovery assessment

The balance recovery protocol was undertaken as reported in Carty et al. (2011). Participants stood barefoot with their feet shoulder-width apart in an upright posture and were subsequently tilted forward, with their feet flat on the ground, until 15, 20 or 25% of body weight (BW) was recorded on a load cell (S1W1kN, XTRAN, Australia) placed in series with an inextensible cable. One end of the cable was attached to a safety harness worn by the participant at the level of their sacrum and the other end was attached to a rigid metal frame located behind the participant. An electric winch, mounted on the frame, was used to adjust the length of the cable until the required force on the cable was achieved. Care was taken to ensure that the cable was aligned parallel to the ground and that participants kept their head, trunk and extremities aligned prior to cable release. The cable was released at a random time interval (2–10 s) following achievement of the prescribed posture and cable force ($\pm 1\%$ BW), through the disengagement of an electromagnet located in-series with the cable. Participants were instructed to relax their muscles while leaning and to regain balance with a single step using the stepping lower limb of their choice, once they perceived that they were falling. The instruction to attempt to recover using a single step was reiterated prior to every trial. A second cable, instrumented with a load cell (S1W1kN, XTRAN, Australia), attached the safety harness to the ceiling, and was used to prevent participants from contacting the ground in the event of an unsuccessful recovery. Centre of pressure location was displayed in real time on a computer monitor and was visually inspected by the investigator to ensure that anticipatory actions (e.g., antero-posterior and medio-lateral weight shifting) were not evident in the period immediately prior to cable release. Following an initial trial at the 15% BW lean magnitude, participants performed 4 trials at each lean magnitude, with block randomisation used to determine the lean magnitude sequence (i.e., 15, 20 or 25% BW) for the 12 trials. For each trial, participants were classified as adopting either a single or a multiple step balance recovery strategy using previously published criteria (Carty et al., 2012a) where a multiple step is deemed to have occurred if a) a second step of any kind by the stepping limb or progression of the non-stepping limb past the stepping foot followed the initial step, b) lateral deviation of the lateral malleolus marker on the non-stepping foot by greater than 20% of body height from its position at cable release and c) if a force greater than 20% was detected in the load cell attached to the ceiling restraint. Following the 12 trials at the 15, 20 and 25% BW lean magnitudes, a number of additional trials were attempted by each participant to determine the Maximal Recoverable Lean Magnitude (MRLM) that they could recover from with a single step. Participants were reassessed at the lean magnitude that they had successfully recovered from using a single step strategy. The cable was then systematically increased in ~1% BW increments until the participant could no longer recover with a single step. Once a participant reached a lean angle from which they could not recover with a single step a further trial was performed and if a single step recovery was still not achieved testing then ceased. One minute of recovery was provided between each trial.

2.4. Spatial–temporal, kinematic and kinetic measures

Trajectories of 51 reflective markers attached to the head, trunk, pelvis, and upper and lower limbs were recorded at 200 Hz using a 10-camera, three-dimensional motion capture system (Vicon Motion Systems, Oxford, UK). Ground reaction force data were simultaneously acquired at 1 kHz using two 900×600 mm piezoelectric force platforms (Kistler, Amherst, USA). A single force platform was located under both feet at cable release, and a second force platform was located anterior of the first platform to record ground reaction forces associated with ground contact of the stepping foot. Marker trajectory and ground reaction force data were filtered using a 4th order, zero-lag, low-pass, Butterworth filter (cut-off frequency = 6 Hz). Joint kinematics and kinetics were determined for both the stepping and stance limbs using freely available open source software OpenSim. A scalable anatomical model consisting of 17 bodies, 17 joints, 94 muscle actuators and 36 degrees-of-freedom (Hamner et al., 2010) with body segment parameter estimates from de Leva (1996) was used as the initial generic model for analysis. Model scaling was performed by fitting the anatomical model to measured 3D marker positions with a high weighting on virtual markers which defined the functional joint centre of the hip, knee and ankle. Functional methods were used to define the hip and knee joint centre according to Besier et al. (2003). The ankle joint centre was defined by the midpoint between medial and lateral malleoli. Residual Reduction Analysis (RRA) was subsequently performed to improve the dynamic consistency between measured ground reaction forces and the mass-acceleration product of the model (Delp et al., 2007). The suggested segment mass properties from RRA were implemented in the model which was then used for kinetic analysis. Lower limb joint moments for the stance and stepping lower limbs during the first step