Gait & Posture 42 (2015) 257–262

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Contribution of lower limb eccentric work and different step responses to balance recovery among older adults

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ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form 17 April 2015
Accepted 18 May 2015

Keywords:
Balance recovery
Knee kinetics
Margin of stability
Available response time

ABSTRACT

Falls during walking reflect susceptibility to balance loss and the individual's capacity to recover stability. Balance can be recovered using either one step or multiple steps but both responses are impaired with ageing. To investigate older adults' ($n = 15$, 72.5 ± 4.8yrs) recovery step control a tether-release procedure was devised to induce unanticipated forward balance loss. Three-dimensional position–time data combined with foot-ground reaction forces were used to measure balance recovery. Dependent variables were; margin of stability (MoS) and available response time (ART) for spatial and temporal balance measures in the transverse and sagittal planes; lower limb joint angles and joint negative/positive work; and spatio-temporal gait parameters. Relative to multi-step responses, single-step recovery was more effective in maintaining balance, indicated by greater MoS and longer ART. MoS in the sagittal plane measure and ART in the transverse plane distinguished single step responses from multiple steps. When MoS and ART were negative (<0), balance was not secured and additional steps would be required to establish the new base of support for balance recovery. Single-step responses demonstrated greater step length and velocity and when the recovery foot landed, greater centre of mass downward velocity. Single-step strategies also showed greater ankle dorsiflexion, increased knee maximum flexion and more negative work at the ankle and knee. Collectively these findings suggest that single-step responses are more effective in forward balance recovery by directing falling momentum downward to be absorbed as lower limb eccentric work.

1. Introduction

Falls during locomotion are a major burden to public health due to substantial medical costs, escalating further in demographically ageing countries [1–3]. Falling risk during walking is due to two interacting processes; (i) the individual's proneness to balance disturbance and (ii) their subsequent ability to recover stability and avoid falling. Ageing is associated with impaired neuromuscular function and reduced capacity for balance recovery [4–9] and in older adults forward balance loss is most frequently observed [10]. The influence of ageing on forward balance recovery using either a single-step or multi-step response has been previously demonstrated [4–6,11,12]. Carty and colleagues, for example, showed that a single-step strategy was most advantageous because longer, faster recovery steps increased the widely accepted measure of dynamic balance, "margin of stability (MoS)" defined as the predicted displacement between the anterior base of support (BoS) boundary and the horizontal centre of mass (CoM) position combined with the velocity factor, "extrapolated centre of mass (XCoM)" [6,13].

In previous work balance was proposed to be secured when the XCoM position was posterior to the lead foot in the sagittal plane. This analytical approach has been justified on the grounds of minimal differences in frontal plane motion, the medio-lateral component of dynamic balance [6]. Influences of medio-lateral balance may, however, remain in *resultant* transverse plane motion, reflecting anterior–posterior and medio-lateral balance with respect to resultant centre of mass (CoM) displacement within the BoS defined by both feet. In the present formulation dynamic balance should, therefore, be examined not only using the more conventional anterior–posterior description but also accounting for medio-lateral component of XCoM displacement thus providing a resultant description of balance in the transverse plane relative to the BoS boundary *between* the two feet.

In addition to the spatial measure of MoS, a further aim of the study was to account for temporal aspects of dynamic balance by incorporating available response time (ART). ART is the estimated time available to arrest the CoM prior to balance loss [14,15]. Consistent with our MoS analysis, ART was computed in both the *sagittal* and *transverse* planes by considering horizontal CoM

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http://dx.doi.org/10.1016/j.gaitpost.2015.05.014
0966-6362/

velocity and margin to the BoS boundary. ART was, therefore, based on both sagittal (ARTs) and transverse plane (ARTt), as with the MoS computation described above. This concept considers the position and velocity of the CoM and can be interpreted as specifying the time available for recovery actions.

In balance control research the recovery limb's kinetics have been examined primarily during the swing phase [11]. Using simulation, rather than experimental data, Wu et al. [16] modelled recovery limb stance phase kinetics following foot contact to determine negative work in power absorption. In the present study it was considered important to extend these findings to determine how, by exploiting stance phase power absorption at the knee and ankle, the recovery limb may also assist in preserving balance by controlling CoM kinematics. Impact forces on the foot are absorbed over time and as shown in Fig. 1(C and D) by integrating the power/time function the negative work associated with balance recovery can be determined. The contribution to balance control by recovery limb knee and ankle power absorption have been investigated [16] but hip power generation may also contribute. While the knee and ankle joints contribute to power absorption, the hip generates positive work that may assist balance recovery indirectly via energy transfer to other joints.

The aim of this investigation was to understand how older adults control lower limb stepping responses to preserve balance following unanticipated forward falling. The association between kinetic/kinematic parameters and dynamic stability measures of the recovery step were determined to reveal the biomechanical adaptations to balance recovery. It was anticipated that when the recovery limb arrested the falling momentum, joint kinetics would reflect the conversion of CoM momentum to eccentric work. Greater eccentric work was hypothesised in single-step responses than for the initial step of multi-step recoveries. Furthermore, spatial (MoS) and temporal (ART) balance measures were hypothesised to be greater in single-step actions.

2. Methods

2.1. Participants

Participants were 15 older adults (72.5 ± 4.8yrs) with stature: 1.70 ± 0.09 m and body mass: 76.0 ± 12.3 kg. They were aged 60 years and over, with no neurological or orthopaedic conditions affecting their ability to ambulate independently. Participants were recruited through local newspaper advertisements and all provided informed consent as approved and mandated by the Victoria University Human Research Ethics Committee.

2.2. Model

Reflective markers (14 mm in diameter) were attached to the participants' upper and lower body including the head, torso, pelvis, bilateral upper arms, forearms, thighs, shanks and feet using anatomical landmarks specified by the Oxford Metrics full body "Plug In Gait" model (Oxford Metrics Group, Oxford, England). As shown in Fig. 1(A), the 13-segment whole body model was then applied in balance recovery data capture [17] using a 10 camera (MX-T 40S, 100 Hz) VICON (Oxford Metrics) three dimensional (3D) motion analysis system and three AMTI (Watertown, MA, USA) force plates (Fig. 1A) sampling at 1000 Hz (one model BP600900TT, and two AMTI model BP508600TT). Prior to evaluation, a relaxed standing calibration trial was captured to allow calculation of joint centre locations. For the static trials Knee Alignment Devices (KADs) were used to assist in locating the knee joint centre and axis of rotation. Several

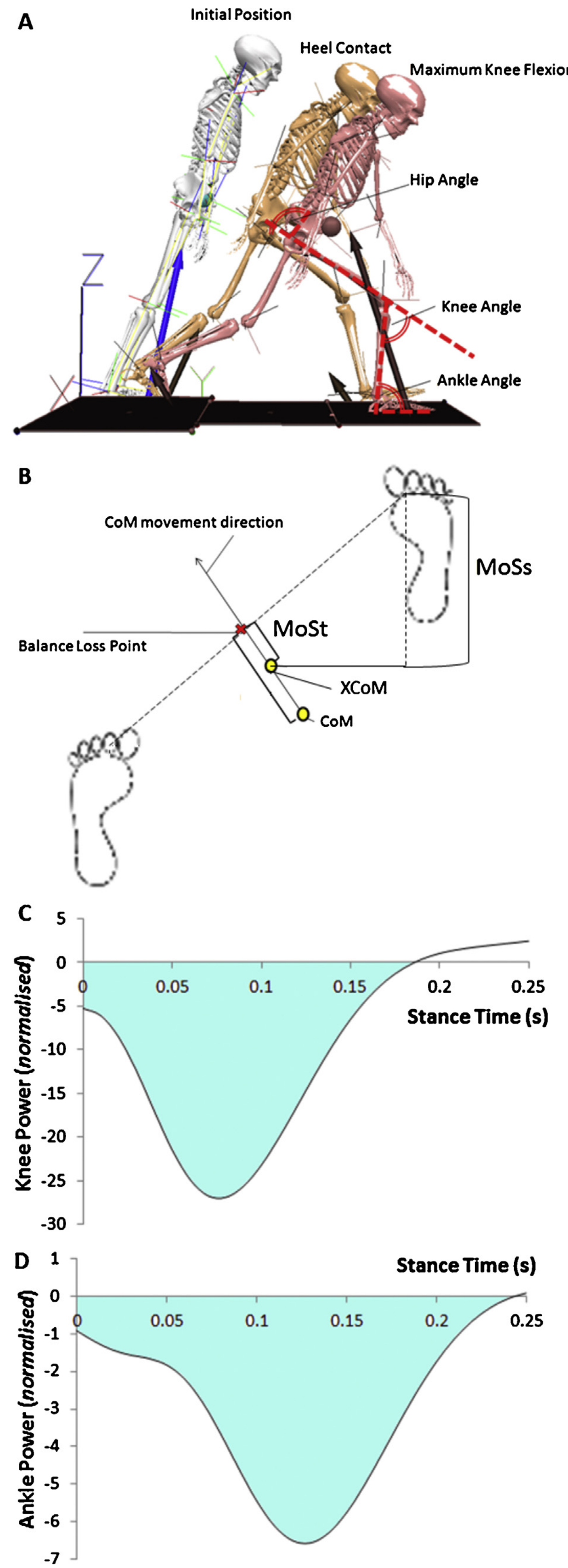

Fig. 1. (A) Illustrations of initial position, foot contact and maximum knee flexion. Whole body (13 segments) model; definition of hip, knee and ankle angle in the sagittal plane; (B) balance parameters (XCoM, CoM, MoSt/MoSs); (C) knee negative work and power absorption; and (D) ankle negative work and power absorption.