Clinical Biomechanics 25 (2010) 873–878

Contents lists available at ScienceDirect

Clinical Biomechanics

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

# The role of strategy selection, limb force capacity and limb positioning in successful trip recovery

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ARTICLE INFO

*Article history:*
Received 25 June 2009
Accepted 17 June 2010

*Keywords:*
Balance
Walking
Lower limb
Elderly
Fall prevention

ABSTRACT

*Background:* Fall occurrence, mainly due to tripping, increases with age. There are two main strategies of trip recovery: elevating and lowering. Strategy selection depends on trip stimulus timing within the swing phase of walking, but the choice and ultimate success of a strategy selection may also depend on individual physical characteristics.

The aim of this study was to investigate: 1) recovery strategy choice by younger and older adults when perturbed in the 'strategy overlap' mid-swing phase, and 2) whether the interaction between recovery limb positioning and recovery limb force capacity determines recovery success in elevating strategy recoveries and accounts for strategy selection.

*Methods:* A group of older (65–75 years) and a group of younger adults (20–35 years) completed a trip recovery protocol in a laboratory environment.

An inverted pendulum model was developed to investigate how walking speed, recovery limb positioning and recovery limb force interacted and influenced successful trip recovery when perturbed in different swing phases.

*Findings:* Older adults always adopted a lowering strategy when perturbed in late mid-swing (60–80%), while younger adults also adopted elevating strategies. Simulations showed that, when perturbed later in swing, a larger recovery step and higher recovery limb force were required for successful recovery.

*Interpretation:* We suggested that a combination of insufficient recovery limb strength, response time and movement speed make it difficult for older adults to achieve a large enough recovery step for a successful elevating strategy recovery when perturbed later in mid-swing.



## 1. Introduction

Approximately one in three people aged over 65 fall at least once a year, mainly due to tripping (Tinetti et al., 1988). Most studies investigating biomechanical aspects of trip recovery have focussed on response time (Bogert van den et al., 2002; Ferber et al., 2002; Hsiao and Robinovitch, 1999; Smeesters et al., 2001), lower limb strength (Pavol et al., 2002; Pijnappels et al., 2008; Wojcik et al., 2001) and muscle activation (Burg van der et al., 2007; Pijnappels et al., 2005).

In early trip recovery (prior to recovery limb ground contact) the body's forward angular momentum will be reduced by the initial stance limb (Pijnappels et al., 2005), arm movement (Roos et al., 2008) and trunk stiffness (Burg van der et al., 2005), while in late trip recovery (during recovery limb ground contact) it is mainly reduced by the actions of the recovery limb and trunk stiffness. Pijnappels et al. (2005) demonstrated that younger adults were generally more capable than older adults to restrain the body's forward angular momentum using the initial support (trailing) limb prior to recovery limb contact. It is however unknown how recovery limb strength and positioning interact to influence recovery success.

The role of the recovery limb may depend on age and on the recovery strategy ('elevating' or 'lowering') employed (Eng et al., 1994). In an elevating strategy the obstructed limb is lifted over the obstacle and in a lowering strategy the obstructed limb is placed prior to the obstacle and the contralateral limb is lifted over the obstacle (Eng et al., 1994). Strategy selection depends on the timing of the trip stimulus within the swing phase of the walk (Schillings et al., 2000). Early swing perturbations result in elevating strategy recoveries (Schillings et al., 2000) as the centre of mass (CM) is posterior to the centre of pressure (CP), leaving time to lift the obstructed limb over the obstacle. Late swing perturbations result in lowering strategy recoveries (Schillings et al., 2000) as the CM is already anterior to the CP and the swing foot is close to the ground; it is therefore easiest to immediately lower this foot to the ground and recover in subsequent steps. Around mid-swing there will be a 'strategy overlap' phase where strategy selection is mechanically not obvious.

Older adults more often adopt a lowering strategy recovery than younger adults (Pavol et al., 2001; Pijnappels et al., 2005), but it is not

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doi:10.1016/j.clinbiomech.2010.06.016

understood why. It could be that they are incapable of or unwilling to use an elevating strategy later in swing when this strategy may become more demanding.

Therefore, the aim of this study was to investigate: 1) the recovery strategies used by younger and older adults when perturbed in the 'strategy overlap' mid-swing phase and the success of these; and 2) whether the interaction between recovery limb positioning and recovery limb force capacity determines recovery success in elevating strategy recoveries and accounts for selection of strategy. Aim 1 was investigated using an experimental approach, while aim 2 was investigated using a simple modelling approach. The angular motion resulting from a trip can be simplified and modelled as pendular movement. Bogert van den et al. (2002) demonstrated, with an inverted pendulum model, that reduced response time was more important for successful trip recovery than lower walking speed. Another inverted pendulum model, by Hsiao and Robinovitch (1999), showed that an interaction between step length, leg strength and step contact time determined the range of possible perturbations that could be recovered from in static lean-release experiments.

We hypothesised that the shift to using lowering instead of elevating strategy recoveries occurs earlier for older than for younger adults. Our second hypothesis was that recovery limb positioning at ground contact influences the muscle force required for successful trip recovery and that appropriate recovery limb positioning becomes essential in situations close to the limits of successful recovery. Our final hypothesis was that a higher recovery limb force capacity (defined as the maximum force which can be developed in the limb) allows for recovery in more challenging trip situations, such as in response to later perturbations, larger perturbations and with non-optimal recovery limb placement.

## 2. Methods

### 2.1. Trip recovery experiment

#### 2.1.1. Protocol

The experimental methods were similar to those described previously (Roos et al., 2008). Briefly, following sample size calculations to allow detection of significant differences in kinematic measures (e.g. step length), female participants were recruited from the local community into a 'younger' group aged 20 to 35 years ($n = 8$) and an 'older' group aged 65 to 75 years ($n = 7$) via poster advertisements and personal contacts. To exclude gender effects only female participants were used. The local NHS (National Health Service UK) research ethics committee approved the experimental procedures (04/Q2001/169 and 05/Q2001/214) and written informed consent was obtained from all participants. Characteristics for the participants are described in Table 1. All participants were recreationally active and healthy, with no BMI (Body Mass Index) above 28, no use of medication that may cause dizziness, no history of repetitive falling and no fear of falling (assessed via the SAFFE questionnaire (Lachman et al., 1998)). Trips were induced in random walking trials, by a custom-built device, at varying time points of the swing phase. The participants were secured in a safety harness to prevent impact with the ground. Kinematic data were collected with a CODA CX1 system (Charnwood Dynamics Ltd., United Kingdom) at 200 Hz.

**Table 1**
Characteristics of the younger and the older participant group with mean values and standard deviations.

| | Age (years) | Body mass (kg) | Height (m) | Lower limb length (m) |
|---|---|---|---|---|
| Younger | 26.1 (3.5) | 63.2 (8.4) | 1.67 (0.04) | 0.89 (8.4) |
| Older | 70.0 (2.5) | 64.2 (4.8) | 1.66 (0.06) | 0.87 (0.02) |

#### 2.1.2. Data analysis

Kinematic data were processed as described in (Roos et al., 2008). The percentage of the swing phase at which trips were induced ($\%_{swing}$) was expressed in relation to the average swing duration of all walking trials. $\%_{swing}$ was calculated by dividing the swing time prior to the perturbation by this average swing duration.

To investigate recovery limb positioning, the recovery step length (RSL) was calculated. This was calculated as the anterior–posterior distance between the ankle coordinates of the obstructed foot at contact with the tripping device and the ankle coordinates of the recovery leg at contact with the force plate, expressed normalised to leg length.

Peak horizontal and vertical ground reaction forces (GRF) during ground contact of the recovery limb were calculated to give an indication of the maximum force in the recovery limb.

For statistical analyses, differences between groups were assessed using independent $t$-tests and relationships between mechanical variables were assessed with Pearson product–moment correlations. Statistical significance was accepted at the $P \leq 0.05$ level.

### 2.2. Trip recovery inverted pendulum simulation model

#### 2.2.1. Model structure

To understand how recovery limb positioning and force capacity influence trip recovery success, a two-dimensional simulation model was developed and its outcomes were compared with experimental results. An inverted pendulum model with similarities to the model by Hsiao and Robinovitch (1999) was used, but it differed from the previous model in that it simulated trip recovery, not balance recovery from static lean-release, and thus it had an initial walking velocity.

The trip recovery model was developed in Simmechanics (Matlab 2007a, The Mathworks). It consisted of a rigid segment (representing the upper body and initial stance limb) with a body mass ($m_{body}$) and height ($h_{body}$). The body CM was placed halfway along the length of the rigid segment. A rotational spring (stiffness $K_{rot}$) at the base of this segment simulated the reduction of the body's forward angular momentum by the initial stance limb. A massless segment with a linear spring (stiffness $K_{lin}$) was attached to the body segment with a fixed hinge joint (hip) at leg length height (Fig. 1). This spring simulated the reduction of the body's forward angular momentum by the recovery limb during the first recovery step. A larger $K_{lin}$ stiffness

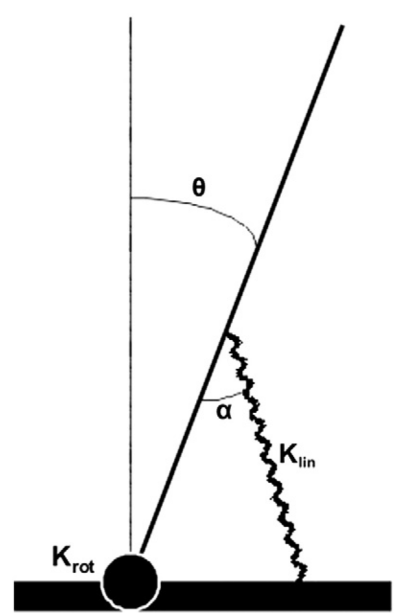


**Fig. 1.** Structure of the inverted pendulum trip recovery model, with $\theta$ the body angle relative to the vertical, $\alpha$ the angle of the recovery limb relative to the body, $K_{rot}$ the rotational spring stiffness, and $K_{lin}$ the linear spring stiffness.