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Quantifying dynamic and postural balance difficulty during gait perturbations using stabilizing/destabilizing forces

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ABSTRACT

Intensity of balance exercises used to reduce fall risk is often poorly quantified. The study aimed to test whether balance difficulty can be rated during gait perturbations against balance difficulty during gait without perturbation, using the stabilizing/destabilizing forces. These forces represent the difficulty to maintain balance as the theoretical forces necessary to cancel body velocity and to set the body into an unstable posture, respectively. Ten healthy subjects walked on a split-belt treadmill, that also generated perturbations. Kinetic and kinematic data were collected during gait at comfortable and fast speeds without perturbation, and in five trials at comfortable speed with perturbations. Perturbations consisted of increasing or decreasing the speed of one belt to three different levels in each direction in a random order during the stance phase of 12 random steps per trial. The difficulty of maintaining balance was measured during the perturbation and the three following recovery steps. Compared to comfortable speed, higher stabilizing and lower destabilizing forces indicated higher balance difficulty during the perturbation step for faster-belt perturbations, and recovery steps for slower-belt perturbations. This was also associated with the center of mass shifted forward, and moving faster, and with the center of pressure closer to the forward limit of the base of support. Difficulty increased proportionally with the intensity of perturbation and was significantly higher for the more intense perturbations than at fast speed. Thus, the stabilizing/destabilizing forces seem adequate to evaluate balance difficulty during gait perturbations and could be used to determine the optimal difficulty for balance rehabilitation.

1. Introduction

Intensity in balance training is often considered in terms of the duration of training (Sherrington et al., 2011; Straudi et al., 2014; Vearrier et al., 2005). However, one could argue that the intensity in terms of the difficulty to maintain balance during the exercises is more important and warrants the use of perturbations to train postural reactions (Farlie et al., 2013).

Perturbation protocols have largely been used in studying balance reactions to determine the organization of postural responses, the determinants of failed or successful responses, and how responses are affected in persons with higher fall risk (Hak et al., 2013; Hof et al., 2007; Horak et al., 1997; Hsiao-Wecksler, 2008; Maki and McIlroy, 2006; Owings et al., 2001; Patla, 2003; Pavol et al., 2001; Wyszomierski et al., 2009). Perturbations in balance training protocols, such as support translation, slipping or tripping devices during gait, treadmill-belt acceleration during standing or walking, have been used with some success to improve postural reactions or balance (Arampatzis et al., 2011; Bhatt et al., 2013; Bhatt et al., 2012; Mansfield et al., 2010; Shimada et al., 2004). However, what intensity is necessary to ensure the most efficient balance training remains an important question. Mansfield et al. proposed to apply the overload principle to balance training in standing by adapting the intensity of platform perturbations depending on the adaptation of individuals' reactions to perturbations (Mansfield et al., 2007; Mansfield et al., 2010). The overload principle states that the level of challenge must be high enough during training to induce an adaptation of the trained system and increase its performance (Mansfield et al., 2007). Perturbations in standing led to improvements in alteration of the base of support (BoS), reaching reactions and foot collisions during balance reactions after training. However, the effects of this training on balance, fall risk and rate, or level of activity and participation have not been evaluated, nor the effective overload quantified.

Few training programs have used perturbations during gait to improve balance and none of these studies used an intensity of perturbation related to the actual balance abilities of the participants

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as they used standardized perturbations (Bhatt et al., 2013; Bhatt et al., 2012; Shimada et al., 2004). Therefore, perturbation intensity might have been too important, with a high risk of fall, and a potential to affect balance confidence and self-efficacy (Büla et al., 2011; Hadjistavropoulos et al., 2011), or they could have been insufficient, and leading to suboptimal results.

It is thus important to determine the difficulty of a balance task to be able to adapt and test the optimal training intensity to improve balance and postural responses during gait or other functional tasks. The level of challenge of any balance exercise is in general poorly evaluated or reported, likely due to the absence of adequate measure (Farlie et al., 2013). However, the level of challenge can be compared, as recently done between exergames and gait (Duclos et al., 2012) using the concepts of stabilizing and destabilizing forces to measure balance difficulty (Duclos et al., 2009). The stabilizing force (StaForce) represents the difficulty to maintain balance, as a theoretical force necessary to cancel the body kinetic energy between the current position of the center of pressure and the limit of the base of support (BoS): the higher the stabilizing force, the more difficult it is to stop the body displacements, the higher the dynamic difficulty of the task. The destabilizing force (DestaForce) represents the difficulty to maintain balance according to the position of the body. It is the theoretical force necessary to bring the center of mass and center of pressure to the limit of the BoS: the lower the destabilizing force, the easier it is to place the body into an unstable posture, the higher the difficulty of postural balance.

To test whether the level of difficulty of perturbations can be rated against balance required during "regular" gait conditions without perturbation, the objective of the present study was to determine the level of postural, dynamic and global balance difficulty during gait with perturbations using the stabilizing/destabilizing forces and to compare them to balance difficulty during gait at comfortable and fast speeds. We hypothesize that difficulty to maintain balance increases with larger intensities of perturbation, so that this difficulty is higher than at comfortable and even fast gait speed for the more intense perturbations.

2. Methods

Ten healthy subjects were recruited after they gave their informed consent. This group consisted of two men and eight women (22.3 years old (standard deviation (SD) 1.7), 61.5 (9.6) kg, 1.70 (0.07) m).

Gait trials were performed on a split-belt, instrumented treadmill (Bertec Fit®) that recorded ground reaction forces at a sampling frequency of 600 Hz. Three-dimensional body kinematics were recorded using Certus cameras (NDI, Waterloo, Canada) and 75 infrared markers placed on each major body segment (3–6 markers per segment, on the head, trunk, pelvis, upper and lower arms, hands, thighs, shanks and feet) at a sampling frequency of 60 Hz. A digitizing probe was used to locate specific anatomical landmarks within the rigid bodies representing each segment and to define a 3-D link–segment model of the subjects (Winter, 1990), and determine the contour of the shoe soles in reference to the markers placed on each foot. These contours were used during the gait trials to continuously determine the limits of the potential base of support (PBoS) as the vertical projection to the ground of the contours of both soles.

Gait perturbations were generated by a change in the speed of one treadmill belt at a time. Speed changed with an acceleration of ± 20 m/s² during swing phase, detected using ground reaction forces, and came back to comfortable speed during the following swing phase. Six levels of perturbation were defined according to the change in belt speed: 50, 70, 90% (P50, P70 and P90, i.e. reduction of belt speed), 125, 150, and 175% (P125, P150, P175, i.e. increase of speed) of comfortable gait speed. As tested with the first three participants (comfortable gait speed: 1.15–1.4 m/s), the belt speed reached between 96.3 (SD 6.0) and 99.3 (SD 1.2) % of the target speed within 200 ms after the heel contact of the perturbation step, and was less than ± 9.2 (SD 3.6) % away from comfortable speed at the next heel contact on the perturbation belt. A safety harness that did not provide body weight support was worn during every gait trial.

Comfortable speed was determined, in a preliminary trial where the speed of the treadmill was increased by 0.1 m/s every 45 s, as the last speed deemed comfortable by the participants, before the next two increases made the speed uncomfortable (Rosenblatt and Grabiner, 2010). Fast speed was determined as the fastest safe speed the participant could walk, without running. One-minute control trials were performed at comfortable and fast speed before any perturbation to provide reference values of balance difficulty. Then, each perturbation was experienced once for familiarization. Five perturbation trials, 1.5 to 2 min long, were then performed. In each trial, each perturbation level was applied once on each foot, for a total of 12 perturbations per trial, and five repetitions of each level of perturbation on each foot over the experimental session. Perturbations were triggered randomly every 8 to 16 steps (Fig. 1).

2.1. Variables and data analysis

The ground reaction forces and the kinematic data were translated according to the belt velocity at comfortable speed to obtain data relative to the treadmill belt referential (van Ingen Schenau, 1980). For this, each calculated position was translated in the antero-posterior plane by the distance covered by the treadmill between each time frame. Kinetic data were filtered using a fourth-order Butterworth zero-lag filter, with a cut-off frequency of 10 Hz and resampled to 60 Hz to match kinematic data. The position of the global center of pressure (CP), vertical ground reaction forces, potential base of support (PBoS), and position and velocity of the center of mass (CM) were extracted from kinetics and kinematics and used to compute the destabilizing and stabilizing forces (DestaForce and StaForce) and the associated stability index (StaInd) to evaluate postural, dynamic and global balance difficulty during the tasks, respectively (Duclos et al., 2009; Duclos et al., 2012) (see Equations in Supplementary material).

Balance difficulty was assessed during the perturbation step, i.e. the foot on the belt faster or slower than comfortable speed, and during the three following recovery steps, that is, with the two belts back at comfortable speed. Each step started at heel-contact and ended at the next heel-contact of the contralateral foot. Eight consecutive steps were analyzed and averaged from the comfortable and fast gait speed trials. For each step and subject, mean and peak values of the DestaForce (peak: min), StaForce (peak: max) and the StaInd (peak: min) were computed. The means indicate the average difficulty during each step, while the peaks indicates the highest difficulty levels during each step. Additionally, the mean and min values of the distance of the center of pressure Dcp to the limit of the PBoS in the direction of center of mass displacement, the mean and the max velocity of the center of mass (Vcm) and the mean, max and min values of the position of the center of mass (Pcm), relatively (%) to the distance between the posterior and the anterior limits of the PBoS, were computed to further understand how balance difficulty changed with perturbations.

Repeated measures analyses of variance (RM-ANOVAs) and *t*-tests were applied to compare variables between steps and conditions (SPSS software, v.19). Planned contrasts (paired t-tests) were used to compare conditions when a statistically significant effect of the main factor was found. Factorial plans are further detailed in the results section. The level of statistical significance was set at .05.

3. Results

3.1. How did the different levels of perturbation affect balance during gait?

No fall into the harness happened with any of the participants. Lowering and elevating strategies were observed during the

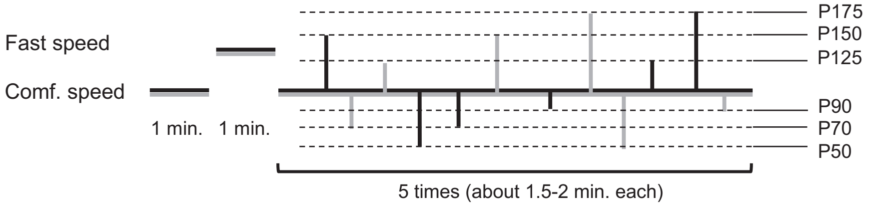

Fig. 1. Schematic representation of the protocol: After two one-minute trials at comfortable (Comf) and fast speed, five trials (about 1.5–2 min long each) were recorded at comfortable speed, during which perturbations were applied in random order under the left (black) or right (gray) foot using 6 different belt speed changes at 175 (P175), 150 (P150), 125 (P125), 90 (P90), 70 (P70) and 50% (P50) of comfortable speed: six different intensities of perturbations, in two directions, were applied on either foot. The number of steps between perturbations was randomly varied between 8 and 16 steps, and the order of the perturbations was randomized between the five trials.