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Dynamic stability control during volitional stepping: A focus on the restabilisation phase at movement termination

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ABSTRACT

This work sought to advance the understanding of dynamic stability control during stepping. The specific intention was to better understand the control of the centre of mass during voluntary stepping, by characterizing its trajectory and intertrial variability. Young participants ($n = 10$) performed five different stepping tasks to vary the challenge to COM control: (1) preferred step, (2) long step, (3) wide step, (4) long and wide step and (5) rapid step. The trajectory of the total body COM during the restabilisation phase was assessed by quantifying the magnitude of incongruity between the peak and final COM position. The intertrial variability of incongruity and the extent to which incongruity was reduced with trial repetition were also evaluated. Interestingly, incongruity was typical during preferred stepping, with a strong bias toward overshoot. In the frontal plane, the magnitude of incongruity and the incidence of overshoot were greater in trials with increased step width. The variability of incongruity did not vary by condition nor was there evidence of adaptive changes. Together, these results suggest that overshoots may represent a strategy linked to gait initiation or to the simplification of reactive control during the restabilisation phase. Further insight into these mechanisms will be gained by examining the kinetic determinants of dynamic stability control.

1. Introduction

The regulation of the relationship between the centre of mass (COM) and base of support (BOS) is a complex control problem, which is essential for the maintenance of upright stability. Various pathological conditions or advancing age, however, can affect the ability to maintain dynamic stability, thereby increasing the risk of falls [1,2]. The challenges to dynamic stability are manifest in tasks such as voluntary gait initiation [3–7], termination [5,8], turning [9] and perturbation evoked stepping [10,11] – all of which have been studied extensively.

The control of stepping involves several important phases: initial preparation, step initiation, limb unloading, swing phase, followed by foot-contact and restabilisation. Few studies have focussed specifically on the restabilisation phase of movement, which occurs subsequent to foot contact. This phase is particularly important for the maintenance of dynamic stability, as it may have the most direct influence on the kinematics of the COM after movement initiation. Challenges to control during the restabilisation phase may be evident from the occurrence of multiple step responses when individuals attempt to regain balance by stepping [1,12–14]. Similarly, older adults have been found to require additional steps during unplanned gait termination [15], which may arise from difficulty in regulating the position and velocity of the COM within the BOS after foot contact.

We suggest that the capacity for effectively regulating the kinematics of the COM during the period subsequent to foot-contact to be a central determinant of dynamic stability during both voluntary and reactive stepping. This initial study is focussed on the kinematics of the COM during the restabilisation phase of a voluntarily initiated single step.

The primary hypothesis was that when participants stepped with self-selected step length and width, there would be little incidence of incongruity between the peak COM position and the final, stable, COM position, when examined in either the anteroposterior (AP) or mediolateral (ML) direction (Fig. 1). Operationally, during the restabilisation phase, we expected that the peak COM position would remain within a 95% confidence band around the mean final COM position.

In contrast, it was anticipated that increasing and constraining step length or width would increase the challenges in stability control after foot contact. Correspondingly, we hypothesized that we would observe an increase in incongruity magnitude, greater intertrial variability of incongruity magnitude and an increased proportion of trials in which the COM overshot its final position

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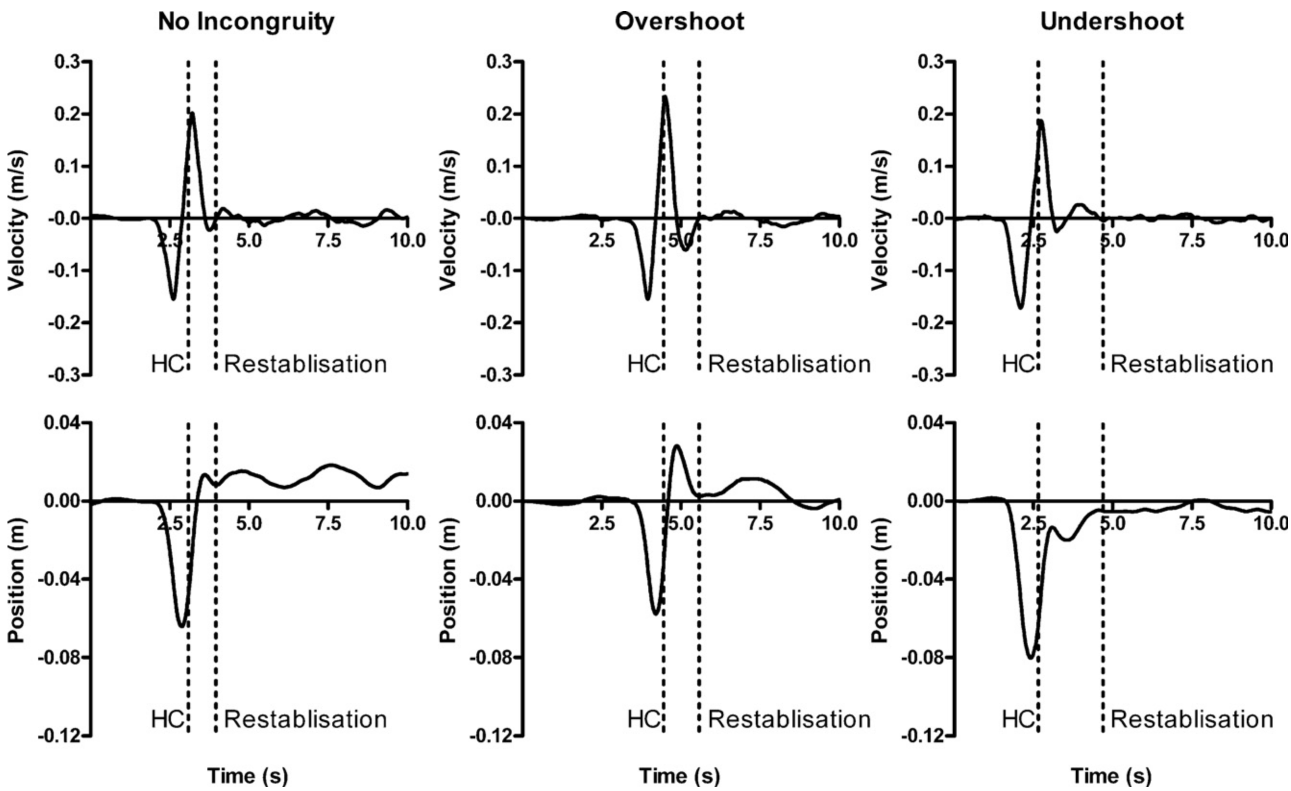

Fig. 1. Representative centre of mass (COM) velocity–time (top) and position–time (bottom) waveforms depicting the three possible incongruity forms: no incongruity (left), overshoot (centre) and undershoot (right). Restabilization signifies the point of restabilization. The restabilization phase occurs between heel-contact (HC) and the point of restabilization.

(Fig. 1). Lastly, with practice during non-preferred stepping conditions, we hypothesized we would observe a reduction in the corresponding AP and ML incongruity over the course of consecutive trials, as individuals became familiar with the movement dynamics during the restabilisation phase. We view this initial work examining dynamic stability control during voluntary stepping in a sample of healthy young adults to be an important precursor to subsequent studies focussed on age-related or disordered control.

2. Methods

2.1. Participants

Ten healthy young male participants (age 24.1 (2.9) years), without balance impairment or history of falls, were recruited from the University population. Male participants were recruited based on ease of anatomical landmark determination and marker placement for the upper body. There is no current evidence that we should expect a difference in stability control between healthy young males and females [16].

2.2. Instrumentation and set-up

Six Vicon MX-3+ cameras (Vicon Motion Systems, Los Angeles, CA) were used to record kinematic data (64 Hz). Four force platforms (Advanced Mechanical Technology, Inc., Watertown, MA), embedded in the laboratory floor in a rectangular array, were used to measure the reaction forces and moments (512 Hz).

Retroreflective calibration markers, of 1 cm diameter, were placed on the participant over anatomical landmarks similar to those described by Hamill and Selbie [17] for the lower limbs and pelvis. Additional calibration markers were placed bilaterally on the upper body, to define local coordinate systems for the trunk, head, upper and lower arms and hands. Rigid clusters containing four markers, placed on the sacrum and trunk, and bilaterally on the feet, legs, thighs, upper and lower arms were used to track the position and orientation of each respective segment.

2.3. Protocol

Participants took part in four different task conditions, which required a single voluntary step with the preferred leg. Ten consecutive trials were collected in each condition:

1. Preferred AP step length/width (AP and ML preferred) (PREF1);
2. **Increased** AP step length (ML preferred) (AP);
3. **Increased** ML step width (AP preferred) (ML);
4. **Increased** AP step length, **increased** ML step width (AP&ML);

Conditions with preferred step length and width were performed as the first trial block (PREF1) and again as the last trial block (PREF2) to assess long-term adaptive changes. The order of the remaining three task conditions (AP, ML and AP&ML) was randomized across subjects. An additional block was conducted in which participants were instructed to step as "rapidly as possible" with preferred step length and width (RAPID). This was included after the completion of all other task conditions to avoid task instruction carryover that may influence speed of stepping in the other task conditions.

Due to constraints on force plate positioning, an absolute target point was prescribed (rather than standardized across subjects), which maximized step length and/or width. Two lengths of adhesive tape were placed on the force platform, parallel and/or perpendicular to the sagittal plane. Average step lengths were increased to 0.73 m; average step widths were increased to approximately 0.50 m, depending on the initial stance width.

Participants began by standing with their feet side-by-side, shoulder-width apart, on separate force platforms. The initial stance width and foot position was standardized within participants. After an auditory command, participants initiated a single step with their preferred leg and, upon landing, remained in a stable position until the end of the trial (approximately 5 s). To counter the possibility of anticipating the auditory command, the intervals at which the next command was given were varied.

2.4. Data analysis

The lower extremity was modelled as a rigid system of independently tracked segments. Segment masses were estimated using Dempster's segment parameters and segment COM positions were estimated using the geometrical model proposed by Hanavan (1964) (cited in Robertson et al. [18]). The total body COM was calculated as a weighted average of all body segments, where each segment was weighted according to its mass proportion.

The COM restabilisation point was defined as the time point after the first zero-crossing, at which the COM velocity waveform entered and remained inside an amplitude bandwidth bordered by +/− two standard deviations of the mean velocity during the last two seconds of the trial. The incongruity magnitude was assessed by calculating the local maximum COM position after foot contact and subtracting the mean of the stable region of the waveform, bound by a two second