



Full length article

Influence of handrail height and fall direction on center of mass control and the physical demands of reach-to-grasp balance recovery reactions

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ABSTRACT

The ability to maintain and recover center of mass (COM) and trunk control after a destabilization is critical for avoiding falls and fall-related injuries. Handrails can significantly enhance a person's ability to recover from large destabilizations, by enabling the person to grasp and apply high forces to the rail to stabilize their COM. However, the influence of handrail height and falling direction on COM control and the demands of grasping are unknown. We investigated the effect of handrail height (34, 38, 42 in.) and fall direction (forward, backward) on COM and trunk control, and the corresponding physical demands of reach-to-grasp balance reactions. Thirteen young adults were destabilized with platform perturbations, and reached to grasp a nearby handrail to recover balance without stepping. COM kinematics and applied handrail forces were collected. COM control was evaluated in terms of: (1) COM range and peak displacement, velocity and momentum in all Cartesian axes; and (2) trunk angular displacement, velocity and momentum in the roll and pitch axes. The physical demands of grasping were estimated via resultant handrail impulse. Compared to forward-directed falling, backward-directed falling was generally associated with greater peak COM and trunk angular displacement, velocity and momentum, along with greater handrail impulse. Higher handrails generally resulted in reduced peak COM and trunk angular displacement, velocity and momentum, as well as reduced handrail impulse. These results suggest that higher handrails may provide a stability advantage within the range of handrail heights tested, with better COM control achieved with lower physical demands of grasping.

1. Introduction

Many falls result from activities that challenge control of a person's center of mass (COM) with respect to their base of support (BOS), such as walking, incorrect weight shifting, tripping, stumbling, or bending [1,2]. The position and velocity of the COM with respect to the BOS can influence fall risk during slipping [3]. Accordingly, the ability to maintain and recover COM and trunk control from destabilizations is critical for avoiding falls and fall-related injuries.

Individuals employ many strategies to control their COM and trunk following balance disturbances. However, the effectiveness of these strategies is heavily context-dependent. For small perturbations, “fixed-support” strategies, such as quickly contracting muscles in the trunk and lower limbs [4,5], can provide stabilizing torques to counteract the rotational forces acting on the COM. Conversely, “change-in-support” strategies (e.g. stepping; reaching to grasp nearby handholds) are often

required to recover from large destabilizations [6]. In situations where stepping reactions may not be reliable (e.g. on stairs or icy walkways), grasping reactions are important for balance recovery. It follows that handrails can significantly enhance ability to recover from balance loss [7], provided that their design enables users to quickly and accurately reach to grasp the rail, and then apply sufficient grasping forces to stabilize their COM [6].

While the value of grasping reactions for balance recovery is well-established, our understanding of how handrail height affects both COM control, and the physical demands of achieving this control during reach-to-grasp reactions, is limited. When considering the inverted pendulum model of balance control, individuals may be able to stabilize their COM while applying lower forces to the handrail when the handrail is high, due to the stabilizing moment advantage gained from higher handrails [8]. Unknown to date is how handrail height impacts COM control following forward and backward balance loss when a

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reach-to-grasp reaction is executed.

This study investigates the effect of handrail height and fall direction on COM control and the corresponding physical demands of reach-to-grasp balance reactions, following forward and backward platform perturbations. We hypothesized that handrail height and fall direction would affect key COM control measures, along with the physical demands of reach-to-grasp reactions in terms of the impulse applied to the rail in response to balance loss.

2. Materials and methods

2.1. Participants

A secondary analysis of a previously-collected dataset was performed [9]. Fifty healthy young adults participated in the larger study, of which 13 participants met our inclusion criteria for analysis in this study (nine males; 18 to 28 years old). To be included in this analysis, participants wore a full-body motion capture marker set and completed all six testing conditions at perturbation magnitudes of 3.5 m/s^2 without falling or stepping (see Sections 2.3 and 2.4 for protocol details). For this study, participant heights ranged from 159 to 193 cm (mean height: $177 \pm 10 \text{ cm}$); weights ranged from 58.1 to 95.3 kg (mean weight: $75.9 \pm 11.4 \text{ kg}$). All participants reported being free of neurological, vestibular and musculoskeletal disorders. The institutional and university's Research Ethics Boards approved this work. All participants provided informed consent.

2.2. Experimental setup

Data were collected using a $5 \text{ m} \times 5 \text{ m}$ laboratory, secured to a robotic platform that can deliver balance perturbations (Fig. 1a). An overhead safety harness protected participants from contact with the floor; slack in the harness line allowed participants to move naturally after balance loss. Participants wore knee guards to minimize possible impact with the floor, and a guard on the right elbow to minimize impact from potential contact with the handrail. Participants recovered balance using a height-adjustable, horizontal handrail (outer diameter: 3.8 cm) (Fig. 1b). Fourteen passive motion capture cameras collected kinematic data (Motion Analysis Inc, Santa Clara, CA). Two load cells (one at either end of the handrail) collected handrail loading data (AMTI MC3A-1000; Advanced Medical Technology, Inc, Watertown, MA).

2.3. Perturbation design

Sudden platform translations disrupted balance: backward platform movements simulated forward-directed falling (Fig. 1d); forward platform movement simulated backward-directed falling (Fig. 1e). Perturbations consisted of square-wave acceleration profiles with a 300 ms acceleration pulse, followed immediately by an equal and opposite deceleration pulse (acceleration magnitude = 3.5 m/s^2 ; peak velocity = 1.1 m/s ; displacement = 0.32 m).

2.4. Protocol

Individual height, weight and right arm length (acromion to fingertip) were measured. Reflective motion capture markers were used to track whole-body COM (see Section 2.5 for details on COM estimation calculations). Rigid marker clusters were secured to the pelvis (cluster at the sacrum), upper body (cluster near the thoracic level of T12), and bilaterally mid-thigh and mid-shank. The distal and proximal ends of these segments with respect to tracking markers were identified in a neutral, stationary pose. Upper limb movement was approximated with tracking markers on the hands (base of the second and fifth metacarpals), wrists (ulnar and radial joints), elbows (medial and lateral epicondyles) and shoulders (acromion; front and back of the

glenohumeral joint). Participants wore standardized athletic shoes during testing.

To begin testing, participants stood erect beside the handrail with their arms relaxed at their sides and feet approximately shoulder-width apart. Their body's center-line was 58% of their right arm length away from the handrail (Fig. 1c), which approximates the distance between the elbow and middle fingertip (adapted from [10]). Foam blocks in front of and behind participants' feet discouraged compensatory stepping.

Upon experiencing a perturbation, participants were instructed to reach to grasp the handrail as quickly as possible to re-stabilize, and to avoid stepping or falling into the harness. All participants received at least four lower-magnitude perturbations for each handrail height, which allowed participants to gain familiarity with the protocol for each handrail height. These perturbations were initially delivered at 2.5 m/s^2 in each direction (forward and backward) and increased in 0.5 m/s^2 intervals before the trials analyzed in this study were reached (at 3.5 m/s^2). If the participant took a step or fell during a familiarization trial, the trial was repeated. This resulted in a minimum of four lower-magnitude perturbations for each handrail height before data was included for analyses. To minimize pre-planning of movements, perturbation timing and falling direction were randomized. Participants counted backward from a randomly-selected start number by an integer between two and nine to distract attention.

For each fall direction, three handrail heights were tested: LOW (86.5 cm/34 in.); MED (96.5 cm/38 in.); and HIGH (106.5 cm/42 in.). 34 in. and 38 in. approximate the lower and upper boundaries of the International Building Code handrail height requirements on stairs and ramps [11], while 42 in. approximates the maximum height of handrails built into stairway landings in the Ontario Building Code [12]. This resulted in six testing conditions, with one trial per testing condition for each participant. The testing order of handrail heights and fall directions was randomized.

2.5. Data processing

Motion capture and handrail force data were sampled at 250 Hz and 1000 Hz respectively, and synchronized offline [13]. Inertial artifacts in the handrail force signals due to platform motion were removed by subtracting force recordings collected without a participant contacting the handrail. COM and trunk angular kinematics were estimated with a twelve-segment, link-segment model (Visual 3D; C-Motion Inc, Germantown, MD). COM kinematics were calculated from a weighted average of trunk, pelvis, upper- and lower-limb segments, with individual segment COMs approximated with existing anthropometric models [14,15].

All kinetic and kinematic signals were filtered with zero-lag, low-pass Butterworth filters with the following orders and cut-off frequencies: 1) load cell signals: 2nd-order/20 Hz; 2) COM kinematics: 2nd-order/6 Hz; 3) trunk angular kinematics: 4th-order/6 Hz. Power analyses revealed that 99% of the signal power was under 6 Hz for all of our analyzed COM and trunk angular position signals. Visual inspection of all filtered kinematic signals further confirmed that the overall signal shape was preserved, particularly where peak position and velocity values were extracted. Force and COM data filters were applied in MATLAB (The Mathworks, Inc, Natick, MA); trunk angular data filters were applied in Visual 3-D. COM position data were differentiated to calculate velocity, and multiplied by individual mass to calculate momentum.

2.6. Data analysis

To evaluate balance control, COM and trunk angular kinematics were analyzed (Fig. 1d/e).

Peak COM displacement, velocity and momentum were calculated 1) along the A-P axis, in the fall direction (Fig. 1f); 2) along the M-L

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