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ORIGINAL ARTICLE

Control of landing under conditions of height-induced threat

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Abstract

Purpose Landing involves a tuned anticipatory control to allow for soft and safe contact with the ground. Fearful situations are known to affect postural control strategies during standing, but it is still unclear how fear interferes with the control of a voluntary dynamic task requiring coordination between posture and movement.

Methods Ground reaction forces, limb movements, physiological arousal, and perceived levels of confidence and fear of falling were recorded when hopping off a box to a platform situated 0.8 m above ground and 3.2 m above ground.

Results Height induced a perceived threat as arousal was augmented by the elevated surface for all subjects. Threat induced by height modifies the way participants land, leading to a stiffer landing, as evidenced by an increased loading rate at touchdown during high threat conditions. Greater psychological and physiological changes are associated with greater changes in the control of landing: individuals that are less confident/more fearful appear to compensate for this stiffer landing, by slowing down their landing.

Conclusion Threatening conditions induces a harder contact to the ground, but the strategy is dependent of the level of confidence/fear. Less confident/more fearful participants are more focused on coping strategy and adopt a more cautious behaviour.

Keywords Hop-off · Fear of falling · Confidence · Arousal · Kinetics

Abbreviations

APSI	Antero-Posterior Stability Index
A_V	Vertical component of the acceleration of the center of mass of the body
BW	Body weight
c2	Mass-specific damping coefficient of the system, calculated during the second part of landing
CoM	Center of mass of the body
EDA	Electro dermal activity
F_V	Vertical component of the ground reaction force
k1	Mass-specific overall stiffness of the spring-mass system, calculated during the first part of landing
k2	Mass-specific overall stiffness of the spring-mass system, calculated during the second part of landing
S_V	Vertical displacement of the centre of mass of the body
t_{AER}	Aerial phase
TD	Touchdown
TO	Take-off
TTS	Time to stabilization
VSI	Vertical Stability Index
V_V	Vertical component of the velocity of the center of mass of the body

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Introduction

Falls are the major cause of fatalities in the construction industry (BLS 2008) with losses in balance being a key factor contributing to fall incidents in roof construction (Cloe 1979; Parsons and Pizatella 1985; Simeonov, Hsiao and Hendricks 2009). Fall risks at an elevated surface include the task and posture of the workers, the distance from the edge of the elevated support surface, the availability of fall protective devices and barriers, and the stability of the structure (Cloe 1979; Suruda et al. 1995; Janicak 1998; Hsiao and Simeonov 2001). Interestingly, experienced roofers have been found to underestimate the risk associated with their job as the habituation to an elevated working environment significantly diminished workers' danger perceptions (Hsiao and Simeonov 2001).

Height intolerance and fear are common in the general population, with a prevalence of 30% (Huppert et al. 2013) and 20% (Depla et al. 2008), respectively. While epidemiological data is lacking in those that work at elevated heights, qualitative data suggests that individuals working at heights often experience feelings of fear and anxiety (Haas 1977), which is accompanied by increased physiological stress with increased working elevation (Min et al. 2012).

Given the known relationships between balance and anxiety in animals and humans (Hogg 1996; Brown and Frank 1997), it is important to understand how anxiety impacts postural performance on elevated surfaces. Fearful situations induced by height have been shown to affect postural control strategies as fearful and non-fearful individuals adopt different postural control strategies (Davis et al. 2009). When threatened during normal standing, fearful individuals typically lean away from the precipice and limit body movement by adopting a stiffening strategy characterized by higher frequency and lower amplitude postural adjustments (Zaback et al. 2016), and increased co-contraction of lower-leg muscles (Carpenter et al. 2001). Similar changes have been observed in construction workers standing on elevated surfaces, with some changes associated with worker experience (Min et al. 2012).

Prior investigations on the effect of height on dynamic balance have been limited to simple tasks, such as maximal reach, one-leg stance, rise-to-toes and walking tasks. When subjects performed a one-legged stance on an elevated surface, the duration of the stance decreased and the limits of stability measured using a maximum functional reach task diminished (Hauck et al. 2008). During a rise-to-toes task at height, anticipatory postural adjustments and maximum movement velocity were decreased, while failure rates increased (Adkin et al. 2002; Zaback et al. 2015, 2016). When walking on elevated surfaces, step length and gait speed are decreased, while step width is increased (Hsiao et al. 2005; Schniepp et al. 2014). However, the effect of heights on performing more complex behaviours that requires co-ordination between balance and movement (e.g. stepping or hopping down, etc.) are less well understood.

Landing from a jump or a hop is a seemingly simple task as healthy individuals can land smoothly without consciously planning the movement. But landing within a given area while maintaining balance is rather complex requiring: (1) the programming of the center of mass of the body trajectory during takeoff to land within a predetermined area; (2) the control of body position during flight; (3) the absorption of the accumulated energy upon impact; and (4) the equilibrium maintenance and restoration of upright stance after landing. It is known that the control of landing is pre-programmed since Melvill Jones and Watt (1971a) have reported anticipatory muscular activity of the gastrocnemius muscle prior to contacting the ground. Absence of anticipatory muscular activity during unexpected sudden falls has been reported to induce a lack of smoothness in the movements of the lower limbs during landing attesting the importance of a preparation to the collision (Melvill Jones and Watt 1971b; Greenwood and Hopkins 1976). Indeed, the central nervous system must predict the instant of touchdown, the characteristics of the forthcoming impact force, and control lower limb joint rotations to dissipate the energy generated during the descent. The control of landing has been shown to be modulated by several factors, such as expertise (Christoforidou et al. 2017), fall height (see review of Santello 2005), ground surface (McKinley and Pedotti 1992), and modified sensory inputs (Gambelli et al. 2015, 2016a, b; Santello et al. 2001). But little is known about the effect of fear on the motor control required to land on the ground.

When hopping off a box, the decrease in potential energy from lowering the centre of mass is converted into kinetic energy throughout the fall. To ensure proper landing of the feet with the ground, i.e. without rebounding or imbalance, the kinetic energy gained during the descent must be dissipated. This implies that the lower limb muscles should absorb that energy and simultaneously allow the body to return to its normal standing position. To do so, the lower limbs must act first as a spring-mass system and then act secondly as a damped harmonic oscillator (Dyhre-Poulsen et al. 1991; Gambelli et al. 2015, 2016a, b). The understanding of how subjects (fearful or not) behave when placed on elevated surfaces will help to improve interventions helping individuals to cope with height and fear, and also help to develop programs for balance-control training to reduce the risk of falls.

Therefore, the purpose of this study was to investigate how changes in height (and consequently changes in fear and balance confidence) affect the motor control of landing after hopping off a small box (44 cm high) in healthy adults. We hypothesized a stiffening strategy would be observed when landing under threatening conditions (i.e. on an elevated surface), eventually leading to the deterioration of the energy absorption mechanism necessary to avoid rebound and thus a less stable landing. Likewise, we hypothesized that greater threat-related changes in balance confidence and fear of falling will be correlated with greater modifications of landing mechanics.

Methods

Participants

Twenty-three healthy young adults (15 females and 8 males, mean ± SD: 28.5 ± 6.4 years, 67.8 ± 12.1 kg, 1.63 ± 0.04 m) volunteered to participate in this study. Participants were physically active but were not currently participating in a varsity or professional sport involving jump-landing tasks (e. g. basketball, volleyball). Exclusion criteria included any self-reported anxiety disorder/extreme fear of height, any neurological, balance or musculoskeletal disorder, any use of medication negatively affecting balance, any recent leg injury (ankle or knee sprain, tibia, fibula or femur bone fracture, during the last 9 months). All experimental procedures were approved by the University of British Columbia (UBC) Clinical Research Ethics Board (ref. H18-00332). Each participant was informed of the experimental procedures and provided written consent prior to the testing session.

Participants attended a single 2 h experimental session at the Neural Control of Posture and Movement Laboratory of UBC. The session included the preparation of the participant, a familiarization condition and testing conditions performed at low and high heights (Fig. 1). The experimental set-up was placed on a hydraulic platform that was positioned at its lowest possible height of 0.8 m above ground for the low condition (LOW) and raised to 3.2 m above ground for the high condition (HIGH). The task was a self-initiated hop off of a box of 44 cm height (Fig. 1), a height commonly used for these types of experiments (45 cm for McKinley and Pedotti 1992; 50 cm for Taube et al. 2012; and 20–60 cm for Christoforidou et al. 2017). Throughout the experiment, participants were barefoot and equipped with a safety harness securely fastened by two climbing ropes connected to a support beam at all times. The supporting rope did not provide any resistance when the participant was performing the hop-off. An examiner was also present beside the participant to provide support in the case of a fall and to assess for landing validity. In addition, railings were placed around the edges of the platform. At no time during the familiarization or experimental procedures were the supporting ropes or the spotter necessary to prevent a fall. Ground reaction forces, limb movements, physiological arousal and self-perceived

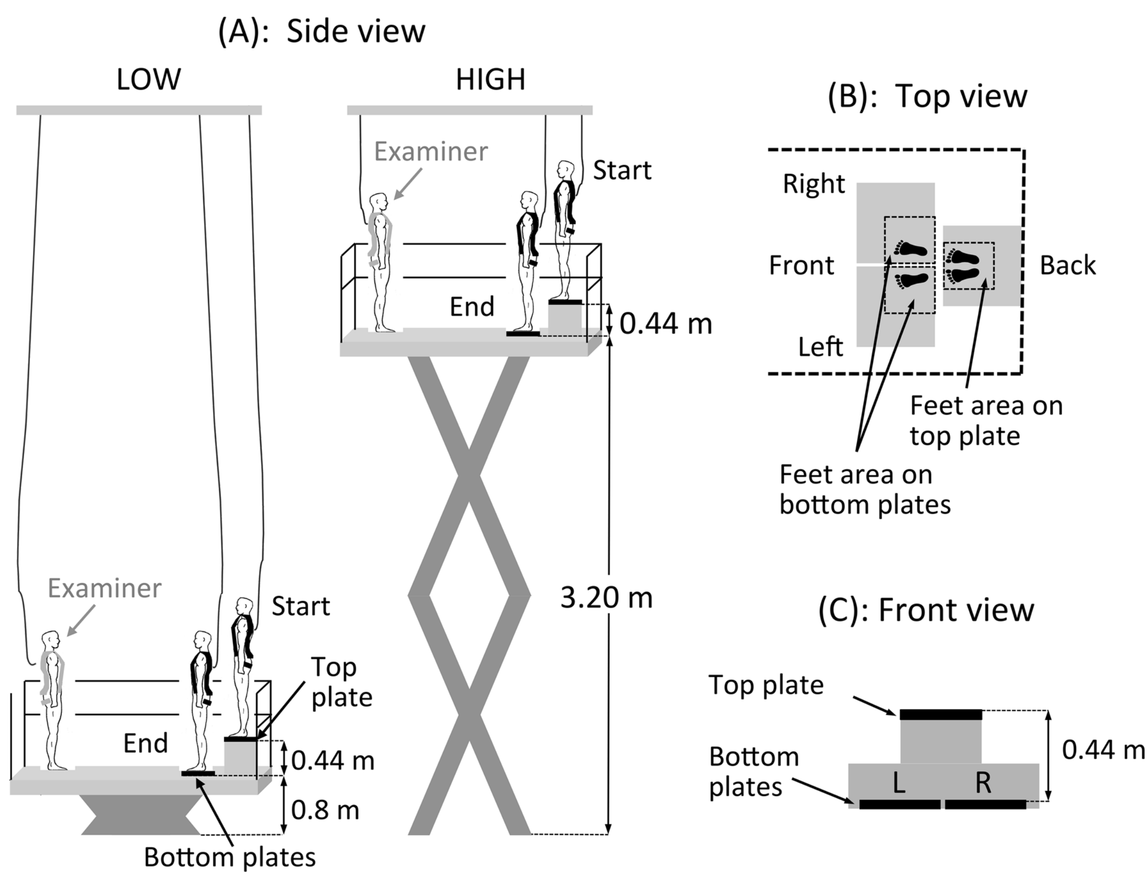

Fig. 1 Experimental set-up with hydraulic platform lift used to create the threat. At first participants stood on the top plate (start) and then jumped off to land on the bottom plates (end). **a** Side view. **b** Top view. Starting and landing areas for the feet on each forceplate. **c** Front view. The height of the hop-off was 44 cm

levels of confidence, anxiety, fear of falling, and attentional focus were recorded.

Procedure

The participants were first familiarized with the task at LOW. They were asked to stand naturally for 40 s with forearms crossed over their chest and toes placed at the front edge of the box. Participants were then asked to practice the hop-offs. The task involved standing still on the box for 5 s, hopping off the box, landing naturally and safely, returning to a stable upright posture, and standing still for 5 s. The familiarization session ended after the participant performed 10 valid landings. To be considered valid, the landing had to meet the following criteria: both feet must land in the targeted landing area (one for each foot, 30 × 30 cm boxes, see Fig. 1); arms must remain crossed over the chest during the task; take-off and landing must be symmetric (involve both feet); and there should be no rebound (bounce) when landing on the ground (i.e. no aerial phase after the first contact with the ground). Validity of landings were evaluated online by the examiner who asked the participant to redo the trial if necessary. No additional directives were given about the speed of movement execution or the style of landing. After familiarization, participants were asked to perform three blocks consisting of a 40 s standing trial followed by 15 valid landing trials. The first block was a practice block at LOW, followed by two experimental blocks at LOW and HIGH height conditions (counter-balanced across subjects).

Apparatus, data collection and reduction

Kinetics variables

Ground reaction forces were collected from forceplates fixed on a 2.1 × 1.5 m hydraulic lift platform (Pentalift, Guelph, CA). A forceplate was fixed at the top of the box (top plate, Fig. 1) and two forceplates were fixed on the landing surface of the hydraulic platform (bottom plates, Fig. 1). The top forceplate recorded the vertical component of the ground reaction force (F_V) from four sensors (Interface SSB-250) located beneath a 32 × 35 cm plate. The bottom forceplates recorded the force components along the vertical axis (F_V), the medial–lateral axis, and the anterior–posterior axis. The forceplate on the left was a 51 × 47 cm AMTI model OR6-7-1000 while the forceplate on the right was a 60 × 40 cm AMTI model BP400600-1000. Data were acquired at a sampling frequency of 1000 Hz (Spike2 CED, UK).

Force plate data (both top and bottom plates) were low-pass filtered at 50 Hz using a dual-pass second order Butterworth filter. The aerial phase (t_{AER}) was defined as the period between take-off (TO, last point where F_V/body weight (BW) > 0.01) and touchdown (TD, last point where F_V/BW < 0.01) (Fig. 2). The vertical component of the acceleration (A_V), velocity (V_V) and displacement (S_V) of the center of mass of the body (CoM) were determined from the vertical component of F_V (Gambelli et al. 2015).

To understand the influence of fear on landing mechanics, the model of Gambelli et al. (2015) was used. In this model, muscle behaviour changes during landing from a spring, to absorb the kinetic energy, to a damper, to dissipate the absorbed energy and to avoid rebound after TD. Therefore, the landing phase was divided into two parts: a first part where muscles were acting like a spring and a second part where muscles were acting like a damped harmonic oscillator. The first part was delimited as the period between TD and the instant at which F_V reached its maximum (F_{VMAX}), and the second phase included the period between F_{VMAX} through the instant at which the CoM reached its lowest point (S_{VMIN}, i.e. when V_V is nil) until the return to the initial standing position. During the first part, F_V increased while S_V decreased, while during the second part F_V decreased while S_V continued decreasing before increasing until the CoM reached its initial standing position. During the first part of landing the mass-specific overall stiffness of the spring-mass system (k1) was computed by a linear regression of the slope of the A_V–S_V curve, and the loading rate was calculated as the slope of the F_V/body weight-time curve. During the second part of landing, the minimal value of F_V (F_{VMIN}) and the lowest position of the CoM (S_{VMIN}) were measured, as well as the mass-specific overall stiffness (k2) and the mass-specific damping coefficient (c2) of the system were estimated using a regression model. In addition the time to stabilization (TTS) was calculated as the time it takes for the participant to return to a stable state following a hop landing (McKinley and Pedotti 1992), where F_V remains within Body Weight ± 2.5% (Fransz et al. 2015). Finally the vertical and anterio-posterior stability indices (VSI, APSI) of Wikstrom et al. (2006) were calculated during the TTS to determine how well balance is maintained as the participant transitions from a dynamic to a static state. A decrease of these indices indicates less GRF oscillations, suggesting a more stable landing.

Kinematics variables

Five infra-red emitting diodes were placed on the participant's skin over the acromion process, greater trochanter, external femoral condyle, lateral malleolus of the ankle and 5th metatarsal phalangeal joint to measure body segment movements. Data were recorded in the sagittal plane (Optotrak Certus, NDI, CA/USA) at 250 Hz, and a cubic spline interpolation was used to up sample the data to 1000 Hz.

The joint angles of the hip, knee, and ankle were calculated as the angle between segments at each instant. The

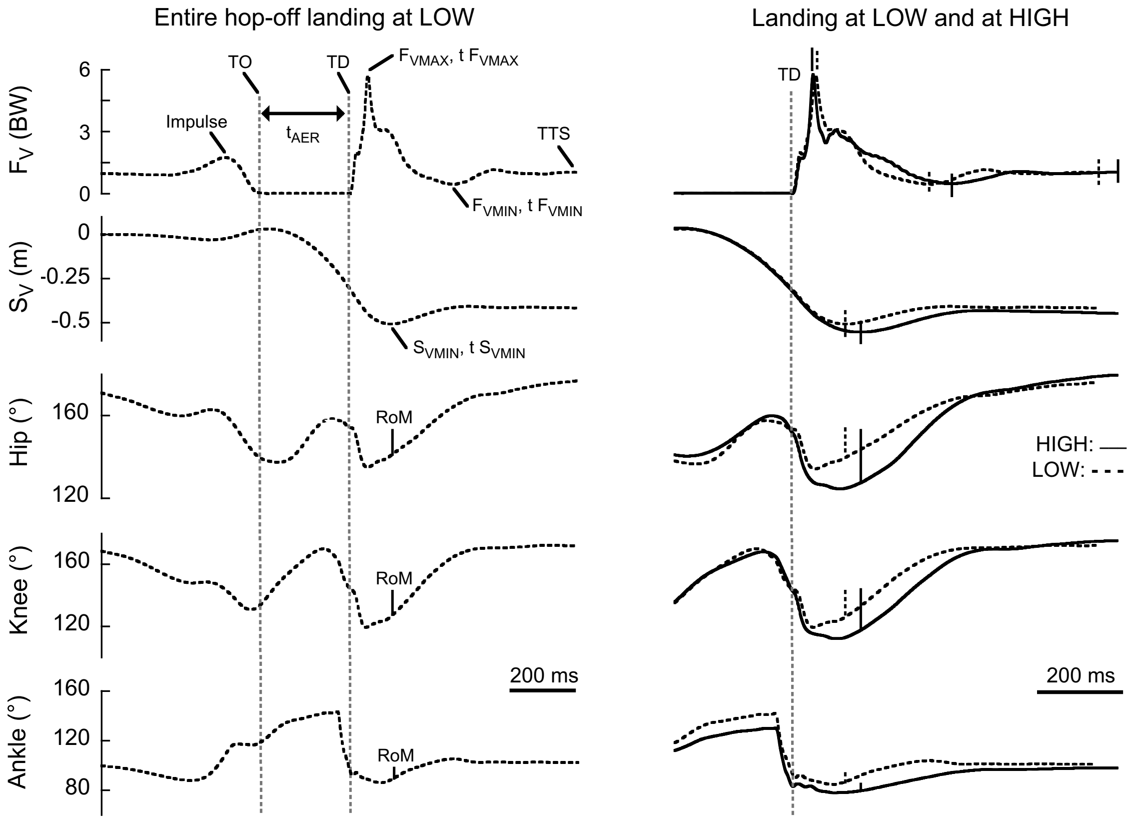

Fig. 2 Individual traces of the kinetics and kinematics of a landing as a function of time (participant #16). Left: entire hop-off landing performed at LOW. Traces start when the participant initiates the hop-off on the top plate and end when the participant returns to a stable position on the bottom plates (time to stabilisation, TTS). Right: landing at LOW (interrupted black line) and at HIGH (continuous black line). Traces start before touchdown and end at TTS. From top to bottom: vertical ground reaction (F_V, BW) and vertical displacement (S_V, m) of the CoM, angle of the left hip, knee, and ankle joints (°). On the left, the aerial phase (t_{AER}) is indicated by the arrow, delimited by the take-off (TO, vertical interrupted line) and the touchdown (TD, vertical dotted line). The maximum and minimum values and timing of the vertical component of the ground reaction force (F_{VMAX}, F_{VMIN}, $t\ F_{VMAX}$, $t\ F_{VMIN}$), the lowest position of the CoM and its timing (S_{VMIN}, $t\ S_{VMIN}$) and TTS are indicated. The range of motion (RoM) during the downward part of the landing (from TD to $t\ S_{VMIN}$) is indicated for the hip, knee and ankle joints

mean values of each angle (°) were calculated for the 40 s quiet standing trial preceding the landings, as well as at different time periods during the landing trials (Fig. 2).

Physiological arousal

To estimate changes in physiological arousal, electrodermal activity (EDA) was recorded at a sampling frequency of 1000 Hz (Spike2 CED, UK) from two surface electrodes placed on the thenar and hypothenar eminences of the right hand (Skin Conductance Unit, Model 2502-SA, CED, UK) and converted into micro Siemens (μS).

The EDA signal was recorded during the 40 s period of the quiet standing preceding each landing session. The signal was low-pass filtered at 2 Hz offline, with a dual-pass second-order Butterworth filter, and used to calculate the mean EDA (EDA_M, μS) and the frequency of EDA peaks (EDA_F, peak min^{-1}) (Zaback et al. 2016).

Questionnaires

Prior to performing each block of trials, participants estimated their level of confidence on maintaining balance and avoiding a fall during the landing task using a scale between 0% (not confident at all) and 100% (completely confident). Immediately after performing 15 valid landings, participants completed a series of questionnaires about their perceived state anxiety [which combined elements of worry (e.g., about losing balance, performing the task incorrectly, etc.) and somatic anxiety (e.g., tense, nervous, heart racing, stomach sinking, etc.)], their fear of falling, and their stability while performing the task, using an incremental scale between 0% (not at all) and 100% (completely) (Hauck et al. 2008). Using the same procedure, participants also completed a questionnaire to measure where they focused their attention during the task ("Appendix"). They rated how much they thought about or directed attention to information related to movement processes (Question 1), task objectives (Question 2), threat-related stimuli (Question 3), self-regulatory strategies (Question 4) and task-irrelevant information (Question 5), based on the five attention focus categories of Zaback et al. (2016) and Johnson et al. (2019). Participants were also invited to write additional comments after the completion of the five items to allow subjects to report things they felt may not have been captured by the five main categories.

Statistical analysis

For the 40 s period of quiet standing preceding the landing trials, the mean values of the variables were calculated for each participant in each condition. For the landing trials, measurements were analysed on a trial-by-trial basis and the mean values of the first seven trials of each landing session were calculated for each participant in order to avoid habituation of the emotional response to prolonged threat exposure (Johnson et al. 2019; Zaback et al. 2016; Adkin and Carpenter 2018).

The primary focus was to analyze how participants modify their control of landing under postural threat. Data were assessed for normality using the Kolmogorov–Smirnov test. As the majority of the data did not follow a normal distribution, the effect of threat was examined for all dependent measures using the Wilcoxon Signed Rank Test (non parametric test) to compare LOW and HIGH conditions.

The secondary focus was to correlate the changes in arousal, perceived level of confidence, fear of falling, anxiety and stability with the landing modifications. Spearman correlations were performed on the differences between HIGH and LOW conditions. Additionally, the relationships between the perceived levels of confidence, fear of falling, arousal and attention focus were also assessed by Spearman correlations. For all analyses, alpha was set at $p < 0.05$.

Results

All participants were able to perform the hop-off task correctly without loss of balance in both LOW and HIGH conditions, i.e. the climbing ropes remained 'slack' and the examiner never intervened. When standing quietly at the beginning of each session, the arousal was significantly increased at HIGH compared to LOW (see EDA_M and EDA_F, Table 1). No effect of height was observed on the body posture, i.e. the angles of the hip, knee and ankle were not modified (Table 1).

The perceived level of confidence evaluated before the task was significantly decreased at HIGH compared to LOW condition (Table 2). Fear of falling and perceived anxiety were significantly augmented at HIGH while the perceived

Table 1 Effect of threat induced by height on quiet stance before doing the task

Variable	LOW mean ± SD (median)	HIGH mean ± SD (median)	*p* value
EDA_M (μS)[a]	27.4 ± 9.7 (25.8)	37.6 ± 16.9 (36.0)	**0.000**
EDA_F (peak min^{-1})[a]	0.14 ± 0.08 (0.13)	0.22 ± 0.07 (0.21)	**0.000**
Hip (°)	187 ± 5 (187)	187 ± 5 (187)	0.316
Knee (°)	177 ± 5 (176)	177 ± 4 (176)	0.592
Ankle (°)	105 ± 5 (106)	105 ± 4 (105)	0.806

Significant differences are indicated in bold

Statistics: Wilcoxon Signed Ranks Test adjusted with Bonferroni correction for multiple tests

[a]No EDA recordings for participant 2

Table 2 Perceived levels of confidence before doing the task, and of anxiety, fear of falling and stability just after the task

Levels of	LOW mean ± SD (median)	HIGH mean ± SD (median)	*p* value
Confidence	83.5 ± 17.0 (90)	71.6 ± 20.5 (80)	**0.0013**
Fear of falling	10.4 ± 15.2 (5)	25.7 ± 24.8 (20)	**0.003**
Anxiety	27.5 ± 23.1 (30)	63.4 ± 49.2 (50)	**0.000**
Stability	81.7 ± 18.9 (80)	73.1 ± 19.7 (80)	**0.023**

Significant differences are indicated in bold

Statistics: Wilcoxon Signed Ranks Test adjusted with Bonferroni correction for multiple tests

Table 3 Results to the attention questionnaire (adapted from Johnson et al. 2019) just after the task (see "Appendix")

Levels of attention redirected to	LOW mean ± SD (median)	HIGH mean ± SD (median)	*p* value
Movement processes (Q1)	4.2 ± 2.3 (4)	4.8 ± 2.1 (5)	0.172
Task objectives (Q2)	5.7 ± 2.5 (7)	6.0 ± 2.1 (7)	0.385
Threat-related simuli (Q3)	2.3 ± 2.0 (2)	2.8 ± 1.8 (2)	0.187
Self-regulatory strategies (Q4)	4.0 ± 2.6 (4)	3.8 ± 2.6 (4)	0.692
Task-irrelevant information (Q5)	2.5 ± 1.7 (2)	2.4 ± 1.7 (2)	0.927

Statistics: Wilcoxon Signed Ranks Test adjusted with Bonferroni correction for multiple tests

level of stability was significantly decreased (Table 3). There was no significant difference across the 5 items of the attention focus questionnaire (Table 3); though participants at HIGH tended to report higher levels of attention to information related to movement processes (Question 1), task objectives (Question 2), and threat-related stimuli (Question 3). Only six subjects wrote additional 'other' information, which on review, would be classified under existing categories of "task irrelevant" such as a) "not touching/damaging the cables while climbing", b) "people watching me in the room", c) "the harness/wires", d) "getting back up on the box", e) "my son's feet", or "movement processes" such as a) "how my feet works when I jump", b) "soreness on the bottom of feet or joints".

Figure 2 presents typical traces of an entire hop-off landing performed at LOW (Fig. 2, left) as well as the landing period at LOW and HIGH (Fig. 2, right). At first, participants stood still in an upright position. Just prior to TO, participants entered into a slight squat before extending their lower limbs to hop-off the box and land on the ground (Fig. 2, left). On average, the impulse to leave the ground was equal to 1.62 ± 0.20 BW (mean ± SD) and the aerial phase t_{AER} lasted 227 ± 84 ms. During t_{AER}, the hip, knee, and ankle joints started to flex. About 120 ms after TD (118 ± 96 ms), the participants hit the ground with a maximum impact F_{VMAX} of 4.11 ± 0.96 BW at a loading rate of 37.0 ± 22.1 N s^{-1}. Participants then reached their lowest position S_{VMIN} (− 0.60 ± 0.07 m, position of the CoM relative to standing before the hop-off) approximately 219 ± 52 ms after TD. Thereafter the vertical component of the force exerted on the ground reached its minimal value F_{VMIN} (0.61 ± 0.14 BW) 545 ± 156 ms after TD. Note that a F_{VMIN} close to 0 indicates that the participant is close to rebound. During the downward motion of the CoM, the range of motion (RoM) of the hip, knee, and ankle joints were respectively 26° ± 16°, 29° ± 16° and 19° ± 16°. Finally participants returned to their standing position by extending their joints. The time to stabilisation (TTS) was 984 ± 208 ms and the vertical stability index (VSI) was 0.431 ± 0.152. During the first part of landing (from TD to F_{VMAX}), the mass-specific stiffness of the lower limbs k1 was 229 ± 81 s^{-2}, while for the second part of landing, k2 was 65 ± 44 s^{-2} and the damping coefficient c2 was 9.9 ± 3.2 s^{-1}.

When landing at HIGH compared to LOW condition, the time to reach F_{VMAX} and the TTS were significantly decreased, while the loading rate and the coefficient k1 were significantly increased (Table 4). No effect of height was observed on the RoM of the hip, knee, and ankle joints during landing (Table 4).

Relationship between landing characteristics and self-reported confidence or fear of falling

Participants who self-reported less confidence at HIGH compared to LOW had a longer time to reach S_{VMIN} and F_{VMIN}, a longer TTS, and a diminished VSI (Fig. 3, Table 5). A similar but opposite relationship between self-reported fear of falling and the same landing kinetics was observed (Fig. 3, Table 5). Confidence and fear of falling were significantly correlated with changes in attention to self-regulatory strategies and threat-related stimuli respectively (Table 6), while arousal was significantly related to the perceived anxiety (Table 5). No other significant correlations between the self-reported measures, arousal or landing variables were observed.

Discussion

The study shows that even with a modest change in emotional state related to the threat of standing on an elevated surface, the central nervous system adjusts the landing strategy. When hopping off a box onto a surface 3.2 m above ground, most participants (16/23) reported being less confident and more fearful and anxious compared to when doing the same task at ground level. These significant changes in self-reported measures with threat were accompanied by significant increases in physiological arousal. At HIGH compared to LOW conditions, subjects employed a stiffer landing strategy which was also shorter. First, we observed an augmentation of the loading rate at touchdown. Second, the time to stabilisation was decreased. Third, the spring-like behaviour was modified, confirming the ability of the central nervous system to change the overall mechanical properties of the lower limb during landing from a spring to a damper (Dyhre-Poulsen et al. 1991; Gambelli et al. 2015, 2016a, b). This ability has already been shown in unusual conditions such as during parabolic flights. For example, in an environment simulated with the equivalent of the moon's gravitational pull, the spring and damping coefficients

Table 4 Kinetic and kinematic variables when landing

	LOW mean ± SD (median)	HIGH mean ± SD (median)	p value
Impulse (BW)	1.62 ± 0.20 (1.62)	1.59 ± 0.19 (1.58)	0.206
t_{AER} (ms)	227 ± 84 (245)	223 ± 90 (244)	0.916
F_{VMAX} (BW)	4.11 ± 0.96 (3.99)	4.15 ± 0.97 (4.14)	0.661
$t\ F_{VMAX}$ (ms)	**118 ± 96 (68)**	**100 ± 110 (66)**	**0.025**
Loading rate (N s^{-1})	**37.0 ± 22.1 (35.1)**	**43.0 ± 22.9 (41.5)**	**0.030**
S_{VMIN} (m)[a]	− 0.60 ± 0.07 (0.59)	− 0.60 ± 0.06 (0.59)	0.276
$t\ S_{VMIN}$ (ms)	219 ± 52 (209)	225 ± 58 (205)	0.751
F_{VMIN} (BW)	0.61 ± 0.14 (0.61)	0.63 ± 0.13 (0.63)	0.157
$t\ F_{VMIN}$ (ms)	545 ± 156 (504)	553 ± 155 (502)	0.810
TTS (ms)	**984 ± 208 (973)**	**953 ± 265 (898)**	**0.045**
APSI	0.015 ± 0.006 (0.137)	0.016 ± 0.01 (0.015)	0.140
VSI	0.431 ± 0.152 (0.397)	0.443 ± 0.175 (0.42)	0.748
k1 (s^{-2})[b]	**229 ± 81 (229)**	**248 ± 88 (240)**	**0.048**
k2 (s^{-2})[b]	65 ± 44 (57)	61 ± 36 (60)	0.749
c2 (s^{-1})[b]	9.9 ± 3.2 (9.6)	9.3 ± 2.7 (9.6)	0.187
Kinematic variables			
RoM of the hip (°)	26 ± 16 (26)	29 ± 14 (27)	0.175
RoM of the knee (°)	29 ± 16 (27)	29 ± 13 (28)	0.705
RoM of the ankle (°)	19 ± 16 (15)	15 ± 13 (13)	0.082

Significant differences are indicated in bold

LOW: $n = 157$ data, HIGH: $n = 161$

[a]S_{VMIN} relative to standing position on top plate before jump

[b]Absolute value are presented

Wilcoxon Signed Ranks Test adjusted with Bonferroni correction for multiple tests

adapted to the gravity level in order to avoid rebounding after landing (Gambelli et al. 2016a). Finally, we observed a stiffer landing behaviour at least for the first part of the task (loading rate, k1). This behaviour was expected as we had hypothesized an increased stiffening strategy based on studies when standing at the edge of on elevated surface (Brown and Frank 1997; Carpenter et al. 2001; Davis et al. 2009).

At an individual level, we were able to identify a significant relationship between the postural control strategies used during landing and the degree of threat-related changes in confidence and fear. The less confident or the more fearful the participant felt, the more they (a) extended the time required to reach the lowest vertical position of COM and minimal vertical force to slow down the landing, (b) extended the time needed to stabilize GRFs, and (c) reduced the amount of vertical GRF oscillations prior to reaching a steady balanced state. Similar evidence of ‘careful’ behaviour has been consistently observed when walking at height, in both young and older adults (Caetano et al. 2009; Delbaere et al. 2009; Brown et al. 2002; Tersteeg et al. 2012; Schniepp et al. 2014) and workers with and without experience working at heights (Hsiao et al. 2005). When walking on elevated surfaces, individuals generally decrease gait velocity and stride length, and increase the double support phase, indicating that a more cautious gait pattern. This ‘slowdown’ strategy was also observed by Yiou et al. (2011), as they reported an increase in the duration of the anticipatory postural adjustment before raising one leg while at 66 cm above ground; qualified by them as a “protective postural strategy”. Therefore, our second hypothesis that greater threat-related changes in balance confidence and fear of falling will be related with greater modifications of the mechanics of landing is confirmed, albeit in the opposite direction to what we expected. In this case, the central nervous system seems to take into account the potentially augmented risk of falling in fearful subjects; leading them to slow down their landing pattern. This cautious behaviour matches that observed in less dynamic tasks, such as rising to toes when positioned at the edge of a 1.6 m elevated surface (Adkin et al. 2002). In this case, the authors observed an increase of the duration of the movement, as well as a reduction of the magnitude and rate of the postural adjustments and subsequent voluntary movement. They also observed an increased number of unsuccessful rises to toes in the more threatening conditions (height of 1.6 m and at the edge). In our cases, all participants succeeded, there were no « missed»/task failures, but participants behave differently depending on the perceived threat. Less confident/

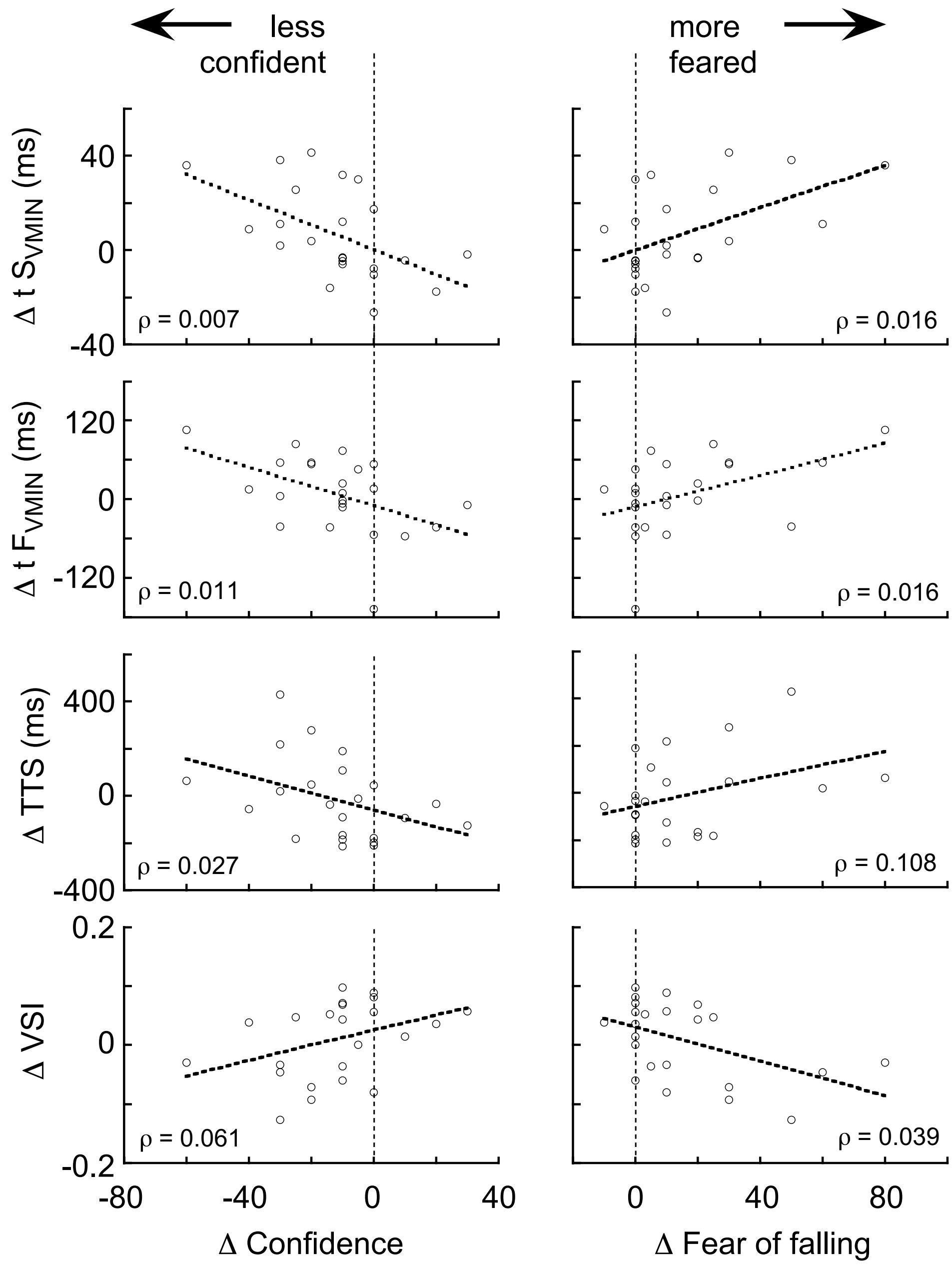

Fig. 3 Linear relationships between kinetic variables (Δ $t\ S_{VMIN}$, Δ $t\ F_{VMIN}$, Δ TTS and Δ VSI) and Δ Confidence and Δ Fear of falling. Differences between HIGH and LOW. Non-parametric correlations, the Rho of Spearman is indicated on each graph

Table 5 Correlations coefficient (Sig 2-tailed) between the arousal and characteristics of landing and perceived levels of confidence, fear of falling, anxiety and stability

	Δ Confidence	Δ Fear of falling	Δ Anxiety	Δ Stability
Δ EDA_M (μS)	− 0.154 (0.483)	0.249 (0.252)	**0.459 (0.027)**	− 0.173 (0.429)
Δ $t\ S_{VMIN}$ (ms)	**− 0.544 (0.007)**	**0.495 (0.016)**	0.146 (0.505)	0.000 (1.000)
Δ $t\ F_{VMIN}$ (ms)	**− 0.518 (0.011)**	**0.497 (0.016)**	0.189 (0.358)	− 0.090 (0.638)
Δ TTS (ms)	**− 0.461 (0.027)**	0.344 (0.108)	0.204 (0.351)	− 0.079 (0.721)
Δ VSI	0.397 (0.061)	**− 0.433 (0.039)**	− 0.264 (0.224)	0.082 (0.709)

Significant differences are indicated in bold

Tests made on the difference (Δ) between HIGH and LOW, $n=23$, except for EDA_M where $n=22$ (no EDA recordings for participant 2). Non parametric correlations are presented: slope and Spearman rho in parenthesis. Bold indicates statistically significant relations. See "Appendix" for details of the Attention focus questionnaire

Table 6 Correlations coefficient (Sig 2-tailed) between responses to the attention questionnaire and the perceived levels of confidence and fear of falling

Attention directed to:	Δ Confidence	Δ Fear of falling
Δ Movement processes (Q1)	– 0.179 (0.414)	0.086 (0.695)
Δ Task objectives (Q2)	– 0.223 (0.306)	0.131 (0.553)
Δ Threat-related stimuli (Q3)	– 0.335 (0.118)	**0.471 (0.023)**
Δ Self-regulatory strategies (Q4)	**– 0.427 (0.042)**	0.389 (0.066)
Δ Task-irrelevant information (Q5)	– 0.119 (0.589)	– 0.087 (0.692)

Tests made on the difference (Δ) between HIGH and LOW, $n=23$, except for EDA_M where $n=22$ (no EDA recordings for participant 2). Non parametric correlations are presented: slope and Spearman rho in parenthesis. Bold indicates statistically significant relations. See "Appendix" for details of the Attention focus questionnaire

more fearful participants seem to take more time to land and return to a stable posture, even if they hit the ground as hard as the more confident/less fearful participants. They also seem more focused on coping strategies to help remain confident, calm (e.g. regulated breathing, purposeful distraction, positive/relaxing thoughts, etc.) compared to more confident/less fearful people, so they—consciously—prefer to avoid automatic responses.

Finally, though a tendency was found to increase the hip's angular range of motion and decrease the ankle's angular range of motion at HIGH, we did not observe a systematic increase in the RoMs (Table 4). This could be due to the fact that the lower limb is a multi-joint segment; i.e. there are several ways to lower the CoM, by acting with different timing on each joint angle (hip, knee, ankle). An analysis of the contribution of the lower limb joint will enlighten this point. Some elements are already available in the literature, such as the study of Devita and Skelly (1992). In their study the authors evaluated the contribution of the lower limb joints in a task very similar to ours: jumps landing from a 59 cm box. They compared soft and stiff landings; i.e. landing on the ground with respectively maximum knee flexion angles of greater than and less than 90° from full extension. They showed that the ankle plantarflexors provided the major energy absorption function, about 44% of the total muscular work done followed by the knee (34%) and hip (22%) extensors. Additionally Zhang et al. (2000) showed that the contribution of the hip joint is augmented compared to the ankle joint in "safer" landing strategy when hop-off height is augmented.

Methodological considerations

One limitation of this study is that there were obvious visible cues, such as railings, all around the participants. Therefore, it may be possible that the availability of such cues may have influenced the postural control of stability, leading to a very controlled strategy. A less secure or more constrained environment could perhaps have led to less skilful control, including less stable landings and more obvious modifications of the control of landing. Future studies should also focus on the threat direction (away or towards the edge), as it has been suggested that "threat-related postural changes provided protection against a loss of balance by limiting body position and movement in the direction of the perceived risk associated with the threat" (Adkin and Carpenter 2018).

A second limitation was that the fear of falling, anxiety, stability and attention focus questionnaires were fulfilled after a block of trials. While this was done to try and reduce exposure time, and avoid response fatigue by probing after each trial, we recognize that the responses, as a result, represent an average of all trials, and thus likely under-estimate responses from the earlier trials.

A third limitation inherent to this kind of protocol is "the healthy effect"; subjects with extreme fear of falling or with vertigo were excluded by definition, and we suspect that some of those with high fear did not respond to the invitation to participate, thus our sampling distribution does not reflect the entire population. It is also to note that we did not consider height-related activities/sports/work experience as explicit exclusion criteria. Despite of those facts, effect of height was observed.

Finally, future studies should focus on testing greater hop-off heights (more than the height of a stool) as it has been shown that the strategy of energy absorption is modified (shift from ankle to hip strategy observed as landing height increased, Zhang et al. 2000). A change in hop-off height could potentially decrease the confidence of the participant and will help to determine the effect of height on the motor control of landing as it still constitutes a controversial factor (Dyhre-Poulsen et al. 1991; Greenwood and Hopkins 1976; Santello and McDonagh 1998; Viitasalo et al. 1998).

Conclusion

Despite findings that workers are more stable than inexperienced participants as observed by Hsiao et al. (2005) using virtual scaffolding models, the way workers behave and the way they adapt to height is a safety concern. The question of the interaction between the apprehension of losing balance and fear of falling when exposed to heights in workers (and others) remains open. Such findings may be useful in modifying elevated work environments and construction procedures to improve workers' postural balance during various construction tasks.

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Compliance with ethical standards

Conflict of interest None of the authors have any conflicts of interest with this study.

Appendix: Attention focus questionnaire, adapted from Johnson et al. (2019)

Appendix: Attention focus questionnaire, adapted from Johnson et al. (2019)

Subject code: _______________ Condition: __________

While completing the landing task, you may have directed your attention toward different information. Please indicate the extent to which you thought about or paid attention to the following:

Trying to consciously monitor or control specific parts of your movement (e.g., pressure under your feet; ankle, leg, trunk, arm or head movement; how much you were moving; how much you were leaning; contractions of your muscles, etc.)

1	2	3	4	5	6	7	8	9
Not at all		Slightly		Moderately		Quite a bit		Very much so

Concentrating on the specific instructions provided to you about the task objectives (e.g., to keep your arms on your chest, to take-off on both feet, to land on both feet, etc.)

1	2	3	4	5	6	7	8	9
Not at all		Slightly		Moderately		Quite a bit		Very much so

Feelings of anxiety or worry (e.g., concern about the possibility or consequences of falling or failing at the task, etc.)

1	2	3	4	5	6	7	8	9
Not at all		Slightly		Moderately		Quite a bit		Very much so

Coping strategies to help remain confident, calm, and/or focused (e.g., regulated breathing, purposeful distraction, positive/relaxing thoughts, etc.)

1	2	3	4	5	6	7	8	9
Not at all		Slightly		Moderately		Quite a bit		Very much so

Thoughts unrelated to landing task (e.g., plans for after study, events from yesterday, trivial environmental distractions, etc.)

1	2	3	4	5	6	7	8	9
Not at all		Slightly		Moderately		Quite a bit		Very much so

Was there anything else that you focused on or thought about when doing the task?

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