Volitional step execution is an ineffective predictor of recovery performance after sudden balance loss across the age range

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Abstract

Rapid stepping to preserve stability is a crucial action in avoiding a fall. It is also an important measure in the assessment of fall-resisting skills. We examined whether volitional step execution correlates with recovery stepping performance after sudden balance loss for adults of different ages. In addition, we investigated whether volitional step performance can discriminate between individuals with high and low balance recovery capabilities, i.e. between those making single versus multiple steps after balance perturbation. Healthy adults (28 young, 43 middle-aged and 26 older; 24 ± 4, 52 ± 5 and 72 ± 5 years respectively) performed a single step in the anterior direction volitionally in response to a mechanical stimulus to the heel. In a secondary stepping task, participants experienced sudden anterior balance loss in a lean-and-release protocol. For both tasks, an optical motion capture system was used to assess stepping kinematics. We found on average 28% shorter reaction times, 46% faster maximal step velocities and 48% higher rates of increase in base of support across all participants after sudden balance loss compared to volitional stepping ($p < 0.001$). There was a significant age-related decline in recovery stepping performance after sudden balance loss: 24/26 older, 15/43 middle-aged and none of the younger adults required two or more steps to regain balance ($p < 0.001$). Multiple- compared to single-steppers had on average 23% shorter step lengths and 12% lower maximal step velocities for the lean-and-release task ($p < 0.01$). Multiple-steppers also had reduced rates of increase in base of support for both stepping tasks (14% for balance recovery and 11% for volitional stepping). Furthermore, in examining the relationship between the results of the two tasks, only weak to moderate correlations were observed for step velocity and rate of increase in base of support ($0.36 \leq r \leq 0.52$; $p < 0.001$). Thus, performance in volitional step execution has a low potential to explain variability in recovery response after sudden balance loss in adults across the lifespan and hence seems less suitable to be used to identify deficiencies in reactive stepping responses necessary to cope with sudden balance disturbances.

Keywords: Aged; falls; reactive balance; motor control; geriatrics

1 Introduction

Falls have become a major public health issue as they can lead to severe clinical conditions, disability or even death in a growing elderly population (Burns & Kakara, 2018; Terroso, Rosa, Marques & Simoes, 2014) and result in substantial medical costs (Florence, Bergen, Atherly, Burns, Stevens & Drake, 2018). This seems even more significant given that the prevalence of falls and fall-related injuries is already increasing by middle-age (i.e. by about the fifth decade of life; Peeters, van Schoor, Cooper, Tooth & Kenny, 2018; Donaldson, Cook & Thomson, 1990). Even when a fall does not cause injury, subsequent fear of falling can lead to lower physical activity levels and lower social participation, substantially affecting quality of life (Stenhagen, Ekström, Nordell & Elmståhl, 2014). Observational research carried out in long-term care centres has shown that most falls in older adults result from balance loss due to incorrect shift of body weight or external hazards (Robinovitch et al., 2013; Yang et al., 2018). A major challenge for falls prevention is to establish methods that allow identification of individuals at higher fall risk who have impaired balance control capability.

The well-established condition for stable stance is that the vertical projection of the body's centre of mass (CoM) lies within the boundary of the base of support (BoS, roughly the area under and between the feet; Woollacott & Shumway-Cook 1996). Disturbances to posture involve rapid compensatory stepping responses to establish a new BoS and recover balance (Hof, 2007; Maki & McIlroy, 1997; Nashner, Woollacott & Tuma, 1979). Notably, recovery stepping performance after a sudden forward fall in a lean-and-release protocol, i.e. the ability to recover balance with a single step, can predict fall risk in older adults (Carty et al., 2015) as well as reactive step training can produce a clinically relevant reduction in falls incidence (~50%; Okubo, Schoene & Lord, 2016 for a review). The capacity to effectively increase the BoS in a *reactive* manner in order to preserve stability is a crucial assessment of fall-resisting skills and important for the development and evaluation of fall prevention programmes.

Previous studies focusing on volitionally-controlled stepping actions to a non-destabilizing cue showed markedly longer stepping reaction times in older compared to younger adults (Kurz, Berezowski & Melzer, 2013; Luchies et al., 2002; Melzer & Oddsson, 2004), with longer step execution times coinciding with a higher future fall risk for the older group (Melzer, Kurz, Shahar & Oddsson, 2010). Moreover, the same experimental protocols revealed slower intentional stepping in people with a history of falls (Lord & Fitzpatrick, 2001). In these studies, however, even when the required weight shift was not known prior to the task (i.e. which stepping leg was to be used), the instructed stepping actions could be well anticipated and controlled by the participants. Given the unpredictable nature of daily life falls, one might argue that valid fall-resisting skills assessment rather must involve low levels of task certainty, as for sudden postural threats, and provoke reactive stability control mechanisms. Data from a previous investigation (Luchies, Wallace, Pazdur, Young & DeYoung, 1999) do indeed suggest that the performance during a volitional step task fails to estimate older adults' ability to respond quickly to sudden balance loss (i.e. age differences in volitional stepping but similar balance recovery performance). These results contrast with current knowledge of an age-related decline in the recovery due to sudden anterior balance loss (Arampatzis, Karamanidis & Mademli, 2008; Karamanidis & Arampatzis, 2007; Karamanidis, Arampatzis & Mademli, 2008; König, Epro, Seeley, Potthast & Karamanidis, 2019). Moreover, in line with these studies, Lee, Gadareh and Bronstein (2014) revealed similar age-related differences in both volitional and balance recovery stepping responses. Thus, the association between these stepping performances, as well as whether balance recovery stepping may have some advantage over volitional step assessment in estimating a person's reactive balance recovery performance, remains unclear in adults over a wide age range.

The present study investigated the relationship between volitional and balance recovery stepping for a large subject pool (*n* = 97) of varying age. In addition, we aimed to assess whether volitional step characteristics can discriminate between individuals showing single- or multiple-stepping behaviour after sudden loss of balance in a lean-and-release protocol, i.e. between high and low recovery stepping performance. We hypothesized: (i) that there are differences and only moderate correlations in the spatial-temporal stepping characteristics (reaction time, rate of increase in BoS and maximal step velocity) for volitional step execution versus recovery stepping after sudden balance loss in the anterior direction and (ii) that single- and multiple-steppers from sudden loss of balance differ in all analyzed spatial-temporal stepping characteristics during balance recovery compared to volitional stepping. Since it has not been well established yet whether an observed decay in recovery stepping performance from a single exposure to sudden balance loss becomes detectable already by middle age nor has it for different stepping conditions, we also focused on age-related interactions for both stepping tasks. Our concern is the extent to which falls risk assessment tasks are tailored to resemble daily life challenges to balance.

2 Methods

2.1 Participants and experimental design

Twenty-eight young, forty-three middle-aged and twenty-six older adults took part in this study (16/28 men, 24 ± 4 yr; 20/43 men, 52 ± 5 yr; 13/26 men, 72 ± 5 yr; mean ± standard deviation is used throughout). The heights and body masses for the groups were: 177.1 ± 4.6 cm and 70.1 ± 10.7 kg for the young; 173.7 ± 11.1 cm and 75.8 ± 13.0 kg for the middle-aged; and 169.8 ± 8.4 cm and 76.0 ± 14.0 kg for the older adults. Exclusion criteria consisted of any neurological or musculoskeletal impairments of the lower limbs (e.g. joint pain during movement). The participants were generally healthy and reported comparable physical activity levels (7.0 ± 3.4, 6.4 ± 3.9 and 6.6 ± 3.2 h/week for young, middle-aged, and older adults respectively). Our participants took part in two different reactive stepping tasks – a volitionally-controlled anterior step to a tap cue on the heel and a secondary lean-and-release task to test balance recovery performance (Figure 1). The study was approved by the ethics committee of the German Sport University Cologne (ethical approval number 141/2017) and met all requirements for human experimentation in accordance with the Declaration of Helsinki (World Medical Association, 2013). All participants provided written informed consent after initial briefing.

Insert Figure 1

2.2 Volitional step task

In order to examine volitional stepping, the participants had to perform a rapid forward step in response to a mechanical cue (see also Halvarsson, Franzén, Olsson & Ståhle, 2012; Melzer, Shtilman, Rosenblatt & Oddsson, 2007; Figure 1A). At the beginning of the test the participants stood on a force plate (60 x 90 cm; Kistler, Winterthur, Switzerland) with their feet shoulder-width apart, keeping a neutral posture. The experimenter then applied a distinct manual tap cue, using a standard reflex hammer, to the heel of the preferred leg for step initiation (Melzer & Oddsson, 2004). Participants were instructed to step forwards as quickly as possible after sensing the heel tap over a predefined target line (25% of individual body height). The mechanical cue did not cause pain or disturb balance enough to initiate a fall. To control for task predictability, the heel tap was applied only after any anticipatory movements had subsided, i.e. antero-posterior and medio-lateral weight shift regulation (recorded via real-time centre of pressure on the force plate). Target step length was chosen in order to require proper stepping actions of the participants, as opposed to small adjustments of foot position. With this arrangement the foot always landed on a second force plate (60 x 90 cm; Kistler, Winterthur, Switzerland) mounted in front of the first. Only one trial with no prior practice trials was performed to ensure novelty of the task.

2.3 Balance recovery step task

Balance recovery performance related to sudden anterior balance loss was analyzed using a lean-and-release protocol (Figure 1B). The task protocol has been described previously in detail (Karamanidis & Arampatzis, 2007; Karamanidis et al., 2008; König et al., 2019). Briefly, the participants stood on the first force plate as described in *Volitional step task* (section 2.2) and, keeping their feet flat on the ground, were gradually inclined forward via a horizontal inextensible cable attached at one end to a belt around the participant's pelvis and at the other end to a custom-built pneumatic release system (see also Do, Breniere & Brenguier, 1982; Thelen, Wojcik, Schultz, Ashton-Miller & Alexander, 1997). The gradual inclination was terminated when a lean angle was achieved that corresponded to a recording of 23 ± 3% of body weight on a load cell placed in series with the supporting cable. After any anticipatory movements had subsided (i.e. antero-posterior and medio-lateral weight shift adjustments, checked via real-time cable loads and centre of pressure on the force plate), the cable was suddenly released without warning after a random time interval of 10 to 30 s. The participants were told to attempt to restore balance within a single recovery step when released, using the limb of their choice (Madigan & Lloyd, 2005). The recovery limb always landed on the second force plate mounted in front of the first one (see also section 2.2 *Volitional step task*). As for the *Volitional step task*, only one trial was performed. The exact forward lean was chosen according to our previous results of the reduced ability of older adults to regain balance within a single recovery step from cable loads of more than 23% body weight (Karamanidis et al., 2008). Participants were protected by a full-trunk safety harness connected to an overhead track, allowing for full range of motion in anterior and lateral directions while preventing contact of the body with the ground (except for the feet).

Recovery stepping behaviours were classified as single- or multiple-stepping according to our previous description (Karamanidis & Arampatzis, 2007). Briefly, participants were classified as single-steppers if only one step was required to regain balance or if a follow-up step of the contralateral limb did not exceed the anterior displacement of the recovery limb. Accordingly, multiple-stepping behaviour was defined as involving any additional step of the recovery limb or if the participant took a contralateral step exceeding the anterior displacement of the recovery limb. Furthermore, multiple-stepping behaviour was deemed to have occurred if a participant made use of the safety harness support (i.e. >

20% of body weight, determined by a second load cell incorporated into the harness suspension cable; Cyr & Smeesters, 2009).

2.4 Data collection and processing

In order to determine the spatial-temporal step characteristics for the two tasks a six-camera motion capture system (Vicon Motion Systems, Oxford, UK; 120 Hz) was used. One retroreflective marker (25 mm diameter) was attached to each of the forefeet. For further processing the 3D-coordinates of the markers were smoothed using a fourth-order digital Butterworth filter with a cut-off frequency of 20 Hz. For each stepping task three events were identified as follows.

(a) Test initiation, i.e. the instant of the tap cue or the release of the participant from the inclined position. The former initiation was registered by a contact sensor attached to the striking surface of the reflex hammer; the latter by a component of the pneumatic brake-and-release system. In both cases an analogue TTL signal (at 1080 Hz) was simultaneously delivered to the Vicon system.

(b) Foot take-off, defined as the instant at which the forefoot marker of the stepping limb reached a threshold velocity of 0.2 m/s in the anterior direction (the anterior direction was used since almost all participants initiated the volitional step with an anterior slide over the ground, hence using the vertical velocity would have failed to identify the initial timepoint of reaction).

(c) Foot touchdown, defined as the instant at which vertical ground reaction force exceeded a threshold level of 20 N.

Based on the identified events, reaction time (b-a) and swing time (c-b) were derived for each trial. The maximal step velocity during swing time and the rate of increase in BoS (anterior forefoot marker displacement of the stepping limb from take-off to touchdown divided by swing time) were also calculated.

2.5 Statistics

The distribution normality of variables was checked before applying statistical analysis using the Kolmogorov-Smirnov test with implemented Lilliefors correction, revealing that all analyzed parameters conformed to normal distributions ($p > 0.05$).

(i) To examine the volitional and balance recovery stepping responses amongst the three age groups (young, middle-aged and older), separate two-way repeated-measures ANOVAs were used to detect differences in reaction time, maximal step velocity and rate of increase in BoS (age and step task as factors). In case of significant main effects or interactions, Duncan post-hoc corrections were applied. Note that a target step length was used for the volitional step task (25% of individual body height) and hence the effect of age on step length was only assessed by means of one-way ANOVA for the lean-and-release task. Furthermore, Pearson product-moment correlation coefficients were computed for reaction time, maximal step velocity and rate of increase in BoS to identify the relationship between volitional and balance recovery stepping responses.

(ii) The participants were classified into two groups (single-stepper and multiple-stepper) based on their recovery stepping behaviours for the lean-and-release task. Differences in the number of single- or multiple-steppers between age groups were analyzed using separate chi-squared (χ^2) tests of independence. Independent samples *t*-tests were used to examine differences between single- and multiple-steppers in step length (lean-and-release task only), reaction time, maximal step velocity and rate of increase in BoS for the two stepping tasks. The level of significance was set at $\alpha = 0.05$, with all results presented as mean and standard deviation. All statistical analyses were conducted using Statistica software (Release 10.0; Statsoft Inc, Tulsa, OK, USA).

3 Results

3.1 Comparison of volitional and balance recovery stepping responses amongst age groups

Assessment of volitional and recovery stepping responses revealed statistically significant task effects for reaction time, maximal step velocity and rate of increase in BoS [$F(1,94) = 203.88$, 1295.30 and 1643.60 respectively; $p < 0.001$], independent of age. All participants ($n = 97$) showed longer reaction times and slower stepping responses for volitional step execution compared to lean-and-release stepping (Figure 2).

Insert Figure 2

Regarding the comparison of stepping responses amongst the three age groups, we found a statistically significant age effect for maximal step velocity [$F(2,94) = 7.95$; $p < 0.001$], independent of stepping task, with lower velocities for older compared to both younger age groups ($0.001 \leq p \leq 0.004$; Figure 2). There was a significant age x task interaction for rate of increase in BoS [$F(2,94) = 3.29$; $p = 0.04$], with lower rates for older compared to younger adults for both stepping tasks ($p < 0.001$). However, lower rates for older adults compared to middle-aged adults were found only for balance recovery stepping ($p < 0.001$). Furthermore, middle-aged adults showed lower rates of increase in BoS ($p = 0.02$) compared to younger adults for the volitional step task (Figure 2). Step length comparison was performed for the lean-and-release task only (note that minimum step length was predefined for the volitional step task) and revealed a significant age effect [$F(2,94) = 11.64$; $p < 0.001$], with lower step lengths for older compared to both younger age groups (Figure 2). Significant positive weak-to-moderate correlations between results for the two stepping tasks were found for maximal step velocity and rate of increase in BoS over all analyzed participants ($n = 97$; $0.36 \leq r \leq 0.52$; $p < 0.001$; Figure 3).

Insert Figure 3

3.2 Comparison of the single- and multiple-stepper subgroups

Thirty-nine participants (fifteen middle-aged and twenty-four older adults) were classified as multiple-steppers after sudden loss of balance in the lean-and-release protocol. There was an age-related decline in the ability to cope with the task across the adult lifespan, with multiple-stepping required more often in middle-aged compared to young adults ($\chi^2 = 12.38$; $p < 0.001$), in old compared to middle-aged adults ($\chi^2 = 21.47$; $p < 0.001$), and in old compared to young adults ($\chi^2 = 46.52$; $p < 0.001$). Since all of the younger adults regained balance within a single step, only middle-aged and older adults were considered for subgroup comparisons (single-stepper versus multiple-steppers).

Assessment of stepping characteristics for the two pooled groups of middle-aged and older adults revealed statistically significant differences between single- and multiple-steppers for the recovery stepping response in the lean-and-release protocol. In detail, multiple-steppers showed lower maximal step velocities [$t(67) = 5.64$; $p < 0.001$], lower rates of increase in BoS [$t(67) = 6.29$, $p < 0.001$] as well as shorter step lengths [$t(67) = 6.43$; $p < 0.001$] compared to single-steppers (Figure 4). However, for the volitional step execution task such differences could only be observed for the rate of increase in BoS [$t(67) = 2.72$; $p = 0.01$; Figure 4].

Insert Figure 4

4 Discussion

We aimed to examine the relationship between volitional and balance recovery stepping in young, middle-aged, and older adults. In addition, we aimed to understand whether spatial-temporal characteristics of volitional stepping serve to discriminate between groups or individuals with high or low recovery stepping performance after sudden loss of balance. Our hypotheses were confirmed in that (i) spatial-temporal stepping characteristics of volitional stepping showed only poor to moderate correlation with balance recovery stepping and further that (ii) volitional stepping seems to be limited for evaluation of an individual’s recovery performance to sudden balance loss. Our results appear to indicate advantages in the use of the lean-and-release task in comparison to a volitional step execution to assess balance recovery performance.

Although the two stepping tasks appear to share distinct motor control subtasks aimed at appropriate modification of the BoS in the anterior direction, the stepping actions were remarkably slower (on average by 41%) for the volitional stepping response for all age groups. Moreover, our observed correlations between the two stepping tasks ($0.36 \leq r \leq 0.52$; $p < 0.001$) can be classified as poor to moderate associations, indicating that only 13% to 27% of the variance in volitional step characteristics can be related to the variance in balance recovery stepping performance for the analyzed subject pool ($n = 97$). These results support earlier findings that demonstrate that the performance during a volitional step task fails to estimate older adults' ability to respond quickly to sudden balance loss (Luchies et al., 1999). Thus, in contrast to non-destabilizing mechanical cueing, initial perceptual information evoked by postural disturbance seems to be linked directly to the mobilization of subsequent rapid stepping responses. It is likely therefore that the two types of task require different capabilities of the human neuromotor system. Faster motor output during compensatory limb movements can be explained by reliance principally on lower brainstem and spinal circuits, as suggested by the retained capacity for righting actions in decerebrate and complete-spinalized cats (Honeycutt & Nichols, 2010; Zhong et al. 2012) and the occurrence of corrective stumbling responses in human infants before independent walking (Lam, Wolstenholme, van der Linden, Pang & Yang, 2003). In contrast, there is emerging evidence for at least some involvement of the cerebral cortex in reactive balance control (see Bolton, 2015 and Jacobs & Horak, 2007 for reviews). Identification of circuits involved in operation of the more demanding lean-and-release task cannot be determined from the present experimental setup, but the issue should be examined in future investigations.

We compared subgroups of our participants based on recovery stepping performance (Figure 4). The pooled group of multiple-steppers ($n = 39$) showed diminished balance recovery stepping performance, i.e. they had lower step lengths, reduced step velocities and lower rates of increase in BoS compared to single-steppers (*n* = 30). Multiple-steppers may therefore be predisposed to higher fall risk (Carty et al., 2015). It is worth noting that we did not find differences in reaction time (time from instant of release to foot take-off) between these groups. This indicates that alterations in balance recovery capabilities do not seem to relate to diminished neuromotor control for step initiation rather to timing of muscle activation during the reactive stepping response. Similar results were found for the volitional step execution task, but only for the rate of increase in BoS were there statistically significant differences between single- and multiple-steppers. Volitional stepping therefore seems to be limited for evaluation of an individual's recovery performance to sudden balance disturbance. The limited discriminative capacity of volitional stepping in relation to recovery stepping performance is reflected also in the relatively lower effect size for the difference in rate of increase of BoS for volitional stepping with Cohen's *d* being 0.70 (versus 1.51 for recovery stepping). Nevertheless, volitional stepping may be a helpful addition to tasks tailored to resemble daily life challenges to balance within more holistic approaches to falls risk assessment. For example, a previous study (Lord & Fitzpatrick, 2001) was able to detect longer volitional step execution times for fallers compared to non-fallers.

Our results show a diminished reactive stepping performance for older adults due to an age-related reduction in the ability to increase effectively the BoS, irrespective of task complexity. Interestingly, this reduction appears to be detectable already by middle age. These results are in line with diminished balance recovery responses to tripping during walking in people over 40 years of age reported previously (König et al., 2019; Süptitz, Catalá, Brüggemann & Karamanidis, 2013). Reduced ability of older adults to effectively increase the BoS has been associated with muscle weakness (Karamanidis et al., 2008), though a deterioration in stability control seen for middle-aged and older adults may relate to diminished neuromuscular control with aging rather than a general decline in leg extensor muscle strength (Arampatzis et al., 2008).

A potential limitation of the present study relates to predefinition of step length for volitional step execution. This may affect comparability of stepping responses. However, based on our observations from pilot studies (unpublished data), participants were not asked to place their foot at a fixed distance, rather to step over a normalized minimum target line thus provoking proper stepping actions, as opposed to small adjustments of foot position. In order to overcome this potential drawback, swing times were normalized to individual step length for both tasks. We believe therefore that our results are only affected in absolute terms and that the comparison of data sets remains valid.

5 Conclusions

We conclude that the performance in volitional step execution has a low potential to explain variability in recovery response after sudden balance loss in adults across the lifespan and is less suitable to be used to identify deficiencies in reactive stepping responses necessary to cope with sudden balance disturbances. Therefore, these results point to task-specificity in fall-resisting skills assessment, suggesting that the magnitude of postural disturbance may directly affect an individual's reactive stepping performance

6 Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

7 Competing interests

The authors declare that they have no competing interests.

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9 Authors' contributions

M.K. and K.K. conceived and designed the research; J.W. and M.K. performed the experiments; J.W., M.K., G.E. and K.K. analyzed data; J.W., M.K., G.E., J.S., W.P. and K.K. interpreted the results of experiments; J.W., M.K. and K.K. prepared figures; J.W. and M.K. drafted the manuscript; J.W., M.K., G.E., J.S., W.P. and K.K. edited and revised the manuscript; J.W., M.K., G.E., J.S., W.P. and K.K. approved the final text.

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Figure legends

Figure 1: Stepping tasks. **(A):** volitional stepping in response to a tap cue on the heel. Minimum anterior step length was set at 25% of the individual body height for this task. **(B):** balance recovery stepping after sudden release from a forward inclined position (the lean-and-release task). Lean angles were normalized to individual body weights in order to standardize the level of balance loss.

Figure 2: Spatial-temporal characteristics of volitional (VOL) and balance recovery stepping responses (REC). Data are given for reaction time **(A)**, maximal step velocity **(B)**, rate of increase in BoS [ΔBoS; **(C)**] and step length **(D)** in young (*n* = 28), middle-aged (*n* = 43) and older adults (*n* = 26). Values are expressed as means with SD error bars. Statistically significant differences at the level $p < 0.05$: * = between stepping tasks; † = compared to young adults; ‡ = compared to young and middle-aged adults.

Figure 3: Relationship between volitional (VOL) and balance recovery stepping responses (REC). Data are given for reaction time, maximal step velocity and rate of increase in BoS (ΔBoS) in young (*n* = 28), middle-aged (*n* = 43) and older adults (*n* = 26).

Figure 4: Spatial-temporal characteristics of volitional (VOL) and balance recovery stepping responses (REC) for the pooled groups of single- and multiple-steppers (*n* = 30 and *n* = 39 respectively). Data are given for reaction time **(A)**, maximal step velocity **(B)**, rate of increase in BoS [ΔBoS; **(C)**] and step length **(D)** with values expressed as means with SD error bars. Note that none of the younger adults failed to regain balance within a single step and therefore were not considered for subgroup comparison. * represents a statistically significant group effect ($0.001 \leq p \leq 0.01$).