Characteristics of Step Responses Following Varying Magnitudes of Unexpected Lateral Perturbations During Standing Among Older People– Cross-sectional Laboratory Based Study

Shani Batcir
Ben-Gurion University of the Negev
Guy Shani
Ben-Gurion University of the Negev
Amir Shapiro
Ben-Gurion University of the Negev
Itshak Melzer (itzikm@bgu.ac.il)
Ben-Gurion University of the Negev

Research Article

Keywords: falls, older adults, unexpected balance perturbation, step recovery response, total balance recovery

Posted Date: October 20th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-812212/v1

Abstract

Introduction—The inability to recover from unexpected lateral loss of balance may be particularly relevant to the problem of falls.

Aim—We aimed to explore whether different kinematic patterns and strategies occur in the first recovery step in single-step trials when single step was required to recover from fall and in the multiple-step trials, when more than one step were required to recover from fall. In addition, in the multiple-step trials we examined kinematic patterns of balance recovery where extra steps were needed to recover balance.

Methods—Eighty-four older adults (79.3±5.2 years) were exposed to announced right/left perturbations in standing that were gradually increased to trigger a recovery stepping response. We performed kinematic analysis of the first recovery step of all single-step and multiple-step trials for each participant and of total balance recovery in the multiple-step trial.

Results—Kinematic patterns and strategies of the first recovery step in the single-step trials were significantly dependent on the perturbation magnitude. There was a very small, yet significant increase in timing of recovery step as the magnitude increased. In contrast, the first recovery step of the multiple-step trials showed no significant differences between different perturbation magnitudes; while, in total balance recovery of these trails, we observe a small yet significant difference as the magnitude increased.

Conclusions—The first recovery step of the single-step trials i.e., a relatively low perturbation magnitudes, different kinematic movement patterns were used as perturbation magnitudes increased, suggesting that older adults pre-plan their stepping performance. However, in the first recovery step of the multiple-step trials i.e., high perturbation magnitudes, similar kinematic movement patterns were used at different magnitudes, suggesting a more stereotypical behavior.

Introduction

A sideways fall caused by an unexpected lateral loss of balance is more likely to result in direct ground contact with the greater trochanter, possibly resulting in hip fracture [1–3]. Most research on mediolateral balance reactive control has focused mainly on the first recovery step in mediolateral perturbation and at a specific perturbation magnitude [2, 4–7]. Several research studies have been conducted of older participants exposed to increasing magnitudes of mediolateral perturbations [2,8–16]. In these investigations it was found that in cases in which the perturbation magnitudes were low, a fixed base of support strategies were used to preserve balance. At higher perturbation magnitudes a change base of support strategies were used wheares a single-recovery step respose, and even extra steps were needed to preserve balance, i.e., a multiple-step response. Recently, Fujimoto et al. [12] investigated if balance stability at first-step initiation (i.e., first step lift-off) differed between multiple- and single-stepping responses to lateral perturbations in older adults who received lateral waist-pulls at five different magnitudes of perturbations. They found that compared to younger people, older adults had reduced stability at the first foot contact that was associated with taking additional steps. More recently, Batcir et al. [13] found that older adults who reported several falls showed a significant delay in step initiation duration, and had longer step duration and a larger CoM displacement during single-step trials compared with non-fallers and one-time fallers. In their multiple-step threshold trials, when extra steps were needed to recover balance, the participants who had reported several falls exhibited larger CoM displacements and took a longer time to fully recover from balance loss [13]. It is thought that these stepping responses could also be attributed to the CoM motion state as early as first step lift-off, preceding foot contact [13]. The kinematic characteristics of the first recovery step (e.g., step timing, length, velocity, and acceleration) need to match the requirements for optimal control of stability in different conditions, i.e., perturbation magnitudes [17].

In the present study, we sought to investigate the kinematic patterns of the recovery step in single-stepping responses and the first recovery step in multiple-stepping responses when right/left perturbations systematically increased from very low magnitudes to very high magnitudes in standing. This will provide a clearer understanding of the dynamics of recovery step responses in older people, and can deepen insight into the underlying balance control mechanisms of balance recovery. Earlier, Vlutters et al. [16] exposed young people to right/left and forward/backward pelvic perturbations at various magnitudes at two different treadmill walking speeds (i.e., low and high). They found that foot placement after right/left perturbations was adjusted proportionally to the right/left CoM velocity, where as forward/backward unexpected perturbations did not show a similar response. Recently, Nachmani et al. [18] found that as the perturbation magnitudes increased during self selected treadmill walking, older adults showed very small, yet significant decreases in the timing of the step response, and increased their step length.

To truly demonstrate the existence of different control patterns at different perturbation magnitudes, in our experimental set-up, we adjusted the magnitude of perturbations from very low to a very high, and set different onset timings and directions of the perturbations, i.e., right/left. We hypothesized that older people would show similar timing for their first recovery step initiation and step duration at different perturbation magnitudes, suggesting that the temporal patterns of the recovery step response are stereotypic and almost automatic in nature. We also hypothesized that spatial parameters of the first recovery step such as step length, step velocity, and CoM displacement would be adjusted proportionally to the magnitude of right/left perturbation. In regard to multiple-step trials, i.e., higher perturbation magnitudes, we hypothesized that the total time to recover balance would be adjusted to the magnitude of right/left perturbations and be more adaptive.

Methods

Participants

Eighty-four older adults were recruited for a 2 randomized control trials that were approved by the Helsinki Committee of Barzillai University Medical Center in Ashkelon, Israel (ClinicalTrials.gov Registration number #NCT01439451, initial release 23/09/2011 and ClinicalTrials.gov Registration number

#NCT03636672 initial release 17/08/2018). The analysis was a supplementary study based on the baseline measures of the RCT trials. Participants were independent older adults aged 70 years old and over. The exclusion criteria's were: hip or knee arthroplasty within the prior year, Mini Mental State Examination score (MMSE)<24 [19], visual blindness, vestibular dizziness, severe peripheral neuropathies, severe lower-limbs arthritis, symptomatic orthostatic hypotension, respiratory diseases, Stroke, Parkinson's disease, MultipleSclerosis, Amyotrophic Lateral Sclerosis, cancer under active treatment.

Study protocol

After signing on the consent forms, participants were exposed to 26 random right and left unannounced surface translations that systematically increased from very low to very high magnitudes, detaled description reported in our previous studies [see Batcir et al. [13, 17,] and Supplementary Table 1.

Data analysis

We observationally verified single- and multiple-step responses and classified the first step recovery strategy of these responses separately using the following classification [17, 18]: LLSS – loaded leg side step; ULSS – unloaded leg side step; COS – cross-over step; Leg Abduction; Leg collisions (Col); and Fall events. The leg abduction, Col responses, and unsuccessful balance recovery reactions (i.e., fall events) were not considered in the kinematic analysis.

3D kinematic data were captured in the single- and multiple-step trials with the Ariel Performance Analysis System (APAS, Ariel Dynamics Inc.; CA, USA) using two video cameras that simultaneously recorded the motion of 8 reflective markers that were placed at the anterior midpoint of the ankle joints, Anterior Superior Iliac Spines, acromion processes, and radial styloid processes (see detailed description in [13, 17]). This approach was previously shown to be valid and reliable [21].

The following kinematic parameters were extracted: 1) The step initiation duration in milliseconds (ms), 2) First recovery step duration in ms 3) First compensatory step length in centimeters (cm), and 4). When participants took extra-steps to recover their balance, the following parameters were determined: 5) Total balance recovery duration (ms), 6) Recovery step path length, and 7) Total estimated CoM (eCoM) displacement (cm) – the distance in cm that the eCoM traveled from the initial point prior to stepping to the point where participants completed full balance recovery. This method was described in detail in Batcir et al. [13, 17] who also found excellent inter-observer reliability for these balance recovery parameters ($ICC_{2,1}$=0.917-0.978, p<0.001).

Age, MMSE [19], height, weight, BMI, number of medications taken per day, number of diagnosed diseases, gender proportion, number of falls in the last year, the Fall Efficacy Scale (FES-I) [22], late life function, and disability [23] were also assessed.

Statistical analysis

All data were analyzed with PASW Statistics, version 26.0 (Somers, NY, USA). To examine our hypotheses, we tested the associations between the dependent spatial and temporal parameters of the first stepping response in single-step and multiple-step reactions separately (e.g., step initiation duration, step duration, step length, and step velocity) and the perturbation magnitudes using curve estimation linear regression. Since the step strategies may affect the kinematics of stepping, we adjusted the linear regression models for the first step strategy (ULLS, LLSS, and COS). In addition, we tested the associations between the dependent kinematic variables of the total balance recovery parameters during the multiple-step trials (e.g., total recovery duration, recovery step path length, and total eCoM displacement) and the perturbation magnitudes using curve estimation linear regression, adjusting the models for the first step strategy (ULLS, LLSS, and COS). Statistical significance was set a priori at $p<0.05$).

In order to better understand the mechanisms of balance recovery at increasing magnitudes of perturbation, we used a mosaic plot to explore the first step recovery strategies that were performed in the balance reactions. A mosaic plot is a graphical display of the cell frequencies of a contingency table in which the area of boxes of the plot are proportional to the cell frequencies of the contingency table. The widths of the boxes were proportional to the percentage of step responses performed out of the total stepping reactions. The heights of the boxes were proportional to the percent of the first step strategies used to recover from balance loss at each perturbation level. Comparisons of frequencies of step recovery strategies between single- and multiple-step reactions were made using Chi-square tests.

Results

The participants' characteristics were: mean age 79.3±5.2 years, 70% female (n=59), mean MMSE 28.6±1.4, number of medications a day 3.9±2.1 (range 0–11), number of diagnosed diseases 1.8±1.5, height 159.4±9.7cm, weight 67.8±13.2kg, BMI 26.7±4.0 kg/m^2, 38% (n=32) reported a fall last year (range 0–4 fall events), the FES-I 22.0±7.9, and overall function score in the Late Life Function and Disability Instrument 66.1±8.8. The single-step threshold was 8.2±3.3, and the multiple-step threshold 11.1±3.6.

A total of 798 stepping trials were observed. We excluded 104 trials where the participants performed hip abduction responses and 17 trials where the participants fell into the harness system (unsuccessful balance recovery reactions). Thus, 447 single-step trials and 220 multiple-step trials were included in our analysis. Out of the 84 subjects, 55 completed the protocol (26 perturbation trials), 18 asked to stop before completing the experiment (they performed 20.6±3.9 perturbation trials on average), and with 11 subjects, we encountered technical problems at the end of the study protocol (they performed 22.0±2.3 perturbation trials on average that were successfully analyzed).

Kinematic patterns of step recovery response

Figures 1A and 1B show that in single-step reaction trials, as the perturbation magnitudes were systematically increased, there was a small yet significant increase in step initiation and step duration ($R^2=0.155$, $p<0.001$ and $R^2=0.166$, $p<0.001$, respectively). Additionally, the spatial parameters of recovery stepping, i.e., the step length and average step velocity, showed a larger increase (Fig. 1C, $R^2=0.272$, $p<0.001$ and Fig. 1D, $R^2=0.254$, $p<0.001$, respectively).

In regard to the first recovery step in the multiple-step trials, older adults did not show significant differences in step initiation, step length, or step velocity as the perturbation magnitudes were systematically increased (Figs. 1A' 1C' and 1D', but a very low, yet significant incease for step duration (R^2=0.037, *p*=0.005, Figures 1B').

Figure 2A shows that when multiple steps were needed to recover balance, there was a very low, yet significant increase in the total recovery step duration as the perturbation magnitudes increased (R^2=0.037, *p*=0.005). Also, the spatial parameters of the total balance recovery, i.e., the recovery step path length and the total eCoM displacement, showed a very small yet significant increase as the perturbation magnitude increased (Figs. 2B and 2C, R^2=0.052, *p*=0.001 and R^2=0.044, *p*=0.003, respectively).

The first recovery step strategies in single- and multiple-stepping trials

Mosaic plots in Figure 3 show the frequencies of the strategies performed in the first recovery step in the single-step and multiple-step trials (Figs. 3A, B). In the single-step trials, there was a gradual increase in the performance of LLSS (blue boxes) and leg abduction (yellow boxes) strategies and a concurrent decrease in the ULSS strategy (red boxes). However, when multiple-steps were needed to recover balance (Fig. 3B), the strategy of the first recovery step appeared to be the same along all perturbation magnitudes.

In addition, when we compared the total frequencies of the first recovery step strategies between single- and multiple-step trials (Fig. 3A vs. Fig. 3B, right isolated columns), a significant change in the response patterns was found. While the LLSS, ULSS, and leg abduction strategies were the most dominant in single-step reaction trials, these balance strategies were rarely performed during multiple-step reactions (25.9% vs. 16.7%, *p*=0.004; 49% vs. 12.7%, *p*<0.001; and 17.2% vs. 3.3%, *p*<0.001, respectively). The COS strategy was rarely performed in the single-step reaction trials, but was the main strategy employed during multiple-step reaction trials (8% vs. 56.3%, *p*<0.001). In addition, leg collision (Col) and unsuccessful recovery responses (i.e., a fall into the harness) resulted in all cases in the multiple-step trials.

Discussion

In this study, our hypotheses were partially supported, as during the single-step trials, as the perturbation magnitudes increased, older people showed an extremely small, yet significant increase the timing of their first recovery step, i.e., their step initiation, and step duration (R^2=0.155-0.166, Figs. 1A, B). The spatial parameters, i.e., step length and step velocity, showed a higher increase as the perturbation magnitude increased (R^2=0.272 and 0.254, respectively, Figs. 1C, D). This shows that the first recovery step, especially the spatial parameters, demonstrated a flexible behavior which we defined as the ability to adopt new kinematic movement patterns following changes in task requirements, i.e., the magnitude of perturbation [24]. This suggests that in the single-step trials, an adaptive behavior was used, whereas longer and faster recovery steps were performed as the challenge of the test became greater, i.e., the perturbation magnitudes increased.

The above results are in agreement with Vlutters et al. [16], who found that after exposing young participants to medio-lateral pelvic perturbations at various magnitudes during treadmill walking, the step length, i.e., the foot placement after the perturbation, was adjusted proportionally to the medio-lateral CoM velocity. Luchies et al. [25] suggested that the central nervous system estimates the level of instability following a balance perturbation, selects the appropriate balance recovery response, and preplans the stepping behavior, i.e., the use of one large step to recover balance or the use of several small steps, even before the first step is completed. Pai and Patton [26] and Pai et al. [27] demonstrated that the occurrence of a step depends on the interaction between the CoM position and its velocity. Following their model, stepping is necessary if there is a sufficiently high velocity of CoM displacement, even if the vertical projection of the CoM is located within the base of support (BoS) at step initiation. This also supports the notion that the stepping behavior in the single-step trials in our study where the perturbation magnitudes were relatively low (i.e., the single-step trials) were not stereotypic in nature.

In the present study, we expand current knowledge by exploring balance reactive responses in cases where multiple steps were needed to recover balance, i.e., where the perturbation magnitudes were relatively high. Multiple-step responses were always performed at higher perturbation magnitudes than in the single-step trials; thus, they were more similar to a real-life balance loss threat. Interestingly, in the multiple-step trials, as the perturbation magnitudes increased, older people did not show changes in the timing of their first step initiation (Fig. 1A'), first step length (Fig. 1C'), or first step velocity (Fig. 1D'), and a very minimal, yet significant increase was found for first step duration (Fig. 1B'). This suggests that at high perturbation magnitudes, i.e., during the multiple-steps trials, when participants performed more than one step to recover their balance, their first recovery step performance exhibited a rigid behavior. We define this behavior as the inability to adopt new kinematic movement patterns following changes in task requirements, i.e., at increased perturbation magnitudes, suggesting a more automatic/stereotypical behavior during the first step of the multiple-step trials. However, the total balance recovery parameters which represent the whole balance recovery, showed a significant increase (Figs. 2A-C), which suggests a flexible behavior. Thus, during the first recovery step of the multiple-step trials, older adults pre-plan the kinematics of the extra steps, i.e., foot placements to recover balance trying to effectively "catch" the moving CoM over the BoS.

To fully understand the balance reactive response to increasing magnitudes, it must be noted that the kinematics of the first recovery step in the single- and multiple-step trials may be influenced by the strategy of the first recovery step. Our findings clearly show that during the single-step trials, as the perturbation magnitude increased, the LLSS was increasingly in use, from about 10% at low perturbation magnitudes to about 40% at the highest perturbation magnitudes (Fig. 2A). Meanwhile, the ULSS strategy was decreasingly in use, from about 100% at the lowest perturbation magnitudes to about 10% at the highest magnitudes (Fig. 2B). In the LLSS strategy, there is a need to first unload the loaded leg, and then to swing the loaded leg sideways to perform the recovery step [2, 8]. It was reported earlier that the step initiation duration was delayed about 200ms when the LLSS was performed compared to the unloaded leg strategies [2, 8]. This, in fact, explains our findings that as the perturbation magnitude increased, the step initiation duration of the single-step trials also slightly increased (R^2=0.155, Fig. 1A). Due to the unloading phase of the loaded leg in the LLSS, it took a longer time to initiate and complete the recovery step when the perturbation magnitude increased. This also resulted in a small, yet significant increase in the duration of step execution (R^2=0.166, Fig. 1B). The different strategies that were used as the perturbation magnitudes increased further support the notion that the first stepping response in the single-step trials is flexible in nature and that participants selected a different strategy as the perturbation magnitudes increased (Fig. 2A). Since not only the timing of step initiation increased during the single-step trials, but also the strategies used changed as the magnitudes increased, it appears that older adults pre-plan their stepping performance, and perhaps a learning effect occurred during the experiment.

During the multiple-step trials, where the older adults were exposed to higher perturbation magnitudes, as the magnitudes increased, participants used similar first step strategies. The unloaded leg strategies, i.e., COS and ULSS, were the most commonly used, i.e., these made up about 70% of the strategies used across all perturbation magnitudes, while the LLSS strategy was rarely performed (16.7%) (Fig. 2B). This indicates that when older adults were exposed to large perturbation magnitudes, their strategies of balance responses also show rigid behavior. The COS strategy was performed because high perturbation magnitudes induce a faster CoM displacement to load the standing leg and unload the swing leg, allowing foot-lift of the unloaded leg to "crossover" the loaded leg. Since the initiation duration, step duration, and step length of these recovery strategies was somewhat similar across all perturbation magnitudes of the multiple-step trials (Figs. 1A'-D'), this supports the view that using the COS strategy was best to control the moving CoM during the multiple-step trials at relatively high perturbation magnitudes, and that this response may not be under volitional control, thus, requiring an automatic response during the first recovery step.

Several limitations of this study should be acknowledged. First, the results are based on a sample of older people with a relatively high function level, limiting generalization of these conclusions to frail older adults. Second, in the single-step trials, since the magnitude of unexpected perturbations always occurred in the same order (from low to high perturbation magnitudes), there may have been a learning effect according enabling participants to predict that the next perturbation would be higher. However, this would not have been the case for the multiple-step trials, where the strategies and kinematics were similar across all perturbation magnitudes, and participants did not show different coordination patterns; thus, the results were not influenced by the perturbation order. Third, some may argue that the instructions we gave to the participants, i.e., "react naturally and try to avoid falling", may not have been appropriate, and that more constrained instructions such as "try not to step" or "step as rapidly as possible" would have been more appropriate. But we chose to use the unconstrained instructions since they were likely to be more relevant for exploring the ability of the individual to respond in real-life and are, thus, more ecologically valid.

Conclusions

Results of the present study indicate that at increasing perturbation magnitudes, older people demonstrated a "flexible behavior" in strategies and kinematics of the first recovery step in the single-step trials, i.e., at relatively low perturbation magnitudes. However, the kinematics and strategies of the first recovery step at relatively high perturbation magnitudes showed a "rigid behavior", while the total balance recovery kinematics was adjusted to the perturbation magnitude, suggesting a less stereotypical behavior.

Abbreviations

CoM: center of mass; MMSE: Mini Mental State Examination score; LLSS: loaded leg side step; ULSS: unloaded leg side step; COS: cross-over step; Col: Leg collision; eCoM: estimated CoM; ms: millisecinds; cm: centimeters; cm/sec: centimeters per seconds; BMI: body mass index; FES-I: Fall Efficacy Scale intenational; BoS: base of support.

Declarations

Ethical Statement

The study protocol was approved by Ethics/Helsinki Committee of Barzillai University Medical Center in Ashkelon, Israel, and complies with the Declaration of Helsinki and Good Clinical Practice Guidelines. All methods were performed in accordance with the relevant guidelines and regulations of Helsinki and Good Clinical Practice Guidelines.

Acknowledgements

The authors thank the volunteers who participated in this study and the management of Beit Yona and Ganei Omer, Israel for allowing us to use their facilities.

Authors’ contributions

SB was involved in data analysis and interpretation, and drafting of the manuscript. GS and AS were involved in experimental design, data interpretation, and drafting of the manuscript. IM was involved in planning the experiments, data analysis, interpretation, and drafting of the manuscript. The author(s) read and approved the final manuscript.

Funding

This study was supported by a grant from the Israeli Ministry of Health (2011–056), partially supported by the Helmsley Charitable Trust through the Agricultural, Biological, and Cognitive Robotics Initiative of Ben-Gurion University of the Negev, and partially supported by a grant from the Recanati School Foundation of the Faculty of Health Sciences at Ben-Gurion University of the Negev.

Availability of data and materials

Data will be available upon request.

Ethics approval and consent to participate

Prior to participation, all subjects signed an informed consent form that was approved by the Helsinki Committee of Barzilai University Medical Center in Ashkelon, Israel. The study protocol was approved by the Helsinki Committee of Barzilai University Medical Center in Ashkelon, Israel (ClinicalTrials.gov Registration number clinical registry number NCT01439451).

Consent for publication

Not applicable.

Competing interests

IM and AS developed and built the BaMPer perturbation system that was used in this project. All remaining authors have nothing to declare.

References

1. Tsuda T.Tsuda T. Epidemiology of fragility fractures and fall prevention in the elderly: a systematic review of the literature. Curr Orthop Pract. 2017 Nov;28(6):580-585.
2. Maki BE, McIlroy WE (1997) The role of limb movements in maintaining upright stance: the "change-in-support" strategy. Phys Ther 77(5):488-507. Review.
3. Abolhassani F, Moayyeri A, Naghavi M, Soltani A, Larijani B, Shalmani HT. Incidence and characteristics of falls leading to hip fracture in Iranian population. 2006 Aug;39(2):408-13. doi: 10.1016/j.bone.2006.01.144. Epub 2006 Feb 28.
4. McIlroy WE, Maki BE (1996) Age-related changes in compensatory stepping in response to unpredictable perturbations. J Gerontol A Biol Sci Med Sci 51(6):M289-296. doi: 10.1093/gerona/51a.6.m289. PMID: 8914501
5. Mille ML, Johnson ME, Martinez KM, Rogers MW (2005) Age-dependent differences in lateral balance recovery through protective stepping. Clin Biomech (Bristol, Avon) 20(6):607-616. PubMed PMID: 15890438
6. Mille ML, Johnson-Hilliard M, Martinez KM, Zhang Y, Edwards BJ, Rogers MW (2013) One step, two steps, three steps more ... Directional vulnerability to falls in community-dwelling older people. J Gerontol A Biol Sci Med Sci 68(12):1540-1548.
7. Hilliard MJ, Martinez KM, Janssen I, Edwards B, Mille ML, Zhang Y, Rogers MW (2008) Lateral balance factors predict future falls in community-living older adults. Arch Phys Med Rehabil 89(9):1708-1713.

8. Maki BE, Edmondstone MA, McIlroy WE (2000) Age-related differences in laterally directed compensatory stepping behavior. J Gerontol A Biol Sci Med Sci 55(5):M270-7. PubMed PMID: 10819317
9. Crenshaw JR, Kaufman KR (2014) The intra-rater reliability and agreement of compensatory stepping thresholds of healthy participants. Gait & Posture 39(2):810-815. doi: 10.1016/j.gaitpost.2013.11.006. Epub 2013 Nov 15.
10. Bair WN, Prettyman MG, Beamer BA, Rogers MW (2016) Kinematic and behavioral analyses of protective stepping strategies and risk for falls among community living older adults. Clin Biomech (Bristol, Avon) 36:74-82.
11. Müller J, Müller S, Engel T, Reschke A, Baur H, Mayer F (2016) Stumbling reactions during perturbed walking: neuromuscular reflex activity and 3-D kinematics of the trunk–A pilot study. J Biomechan 49(6):933-938.
12. Fujimoto M.,Bair WN, Rogers MW (2017) Single and multiple-step balance recovery responses can be different at first step lift-off following lateral waist-pull perturbations in older adults. J Biomechan 55:41-47.
13. Batcir S, Shani G, Shapiro A, Alexander N, Melzer I (2020) The kinematics and strategies of recovery steps during lateral losses of balance in standing at different perturbation magnitudes in older adults with varying history of falls. BMC Geriatr 20(1):249. doi: 10.1186/s12877-020-01650-4. PMID: 32689965; PMCID: PMC7372810.
14. Winter DA (1995) Human balance and posture control during standing and walking. Gait & Posture 3(4):193-214.
15. Reimann H, Fettrow T, Jeka JJ (2018) Strategies for the control of balance during locomotion. Kinesiol Rev 7(1):18-25.
16. Vlutters M, Van Asseldonk EH, Van der Kooij H (2016) Center of mass velocity-based predictions in balance recovery following pelvis perturbations during human walking. J Exp Biol 219(10):1514-1523.
17. Batcir S, Sharon H, Shani G, et al. (2018) The inter-observer reliability and agreement of lateral balance recovery responses in older and younger adults. J Electromyogr Kinesiol 40:39-47. doi: 10.1016/j.jelekin.2018.03.002. Epub 2018 Mar 16
18. Nachamani H, Shani G, Shapiro A, Melzer I (2020) Characteristics of first recovery step response following unexpected loss of balance during walking—a dynamic approach. Gerontology. 18:1-9.
19. Folstein MF, Folstein SE, McHugh PR (1975) Mini-mental state. A practical method for grading the cognitive state of patients for the clinician. J Psychiat Res 12(3):189-198. doi:0022-3956(75)90026-6
20. Shapiro A, Melzer I (2010) Balance perturbation system to improve balance compensatory responses during walking in old persons. J Neuroeng Rehabil 7:32. doi: 10.1186/1743-0003-7-32
21. Klein PJ, DeHaven JJ (1995) Accuracy of three-dimensional linear and angular estimates obtained with the Ariel Performance Analysis System. Arch Phys Med Rehabil 76(2):183-189.

22. Yardley L, Beyer N, Hauer K, Kempen G, Piot-Ziegler C, Todd C (2005) Development and initial validation of the Falls Efficacy Scale-International (FES-I) Age Ageing 34(6):614-619.
23. Melzer I, Kurz I, Sarid O, Jette AM. (2007) Relationship between self-reported function and disability and balance performance measures in the elderly. J Rehabil Res Dev 44(5):685-691.
24. Wagenaar RC, Holt KG, Kubo M, Ho C (2002) Gait risk factor for falls in older adults: a dynamic prospective. Generation 26:28-32.
25. Luchies CW, Alexander NB, Schultz AB, Ashton-Miller J 1994 Stepping responses of young and old adults to postural disturbances: kinematics. J Am Geriatr Soc 42:506-512.
26. Pai YC, Rogers MW, Patton J, Cain TD, Hanke TA (1998) Static versus dynamic predictions of protective stepping following waist-pull perturbations in young and older adults. J Biomechan 31(12):1111-1118. doi:S0021-9290(98)00124-9 [pii]
27. Pai YC, Patton J (1997) Center of mass velocity-position predictions for balance control. J Biomechan 30(4):347-354. doi:S0021-9290(96)00165-0 [pii]

Figures

Figure 1:

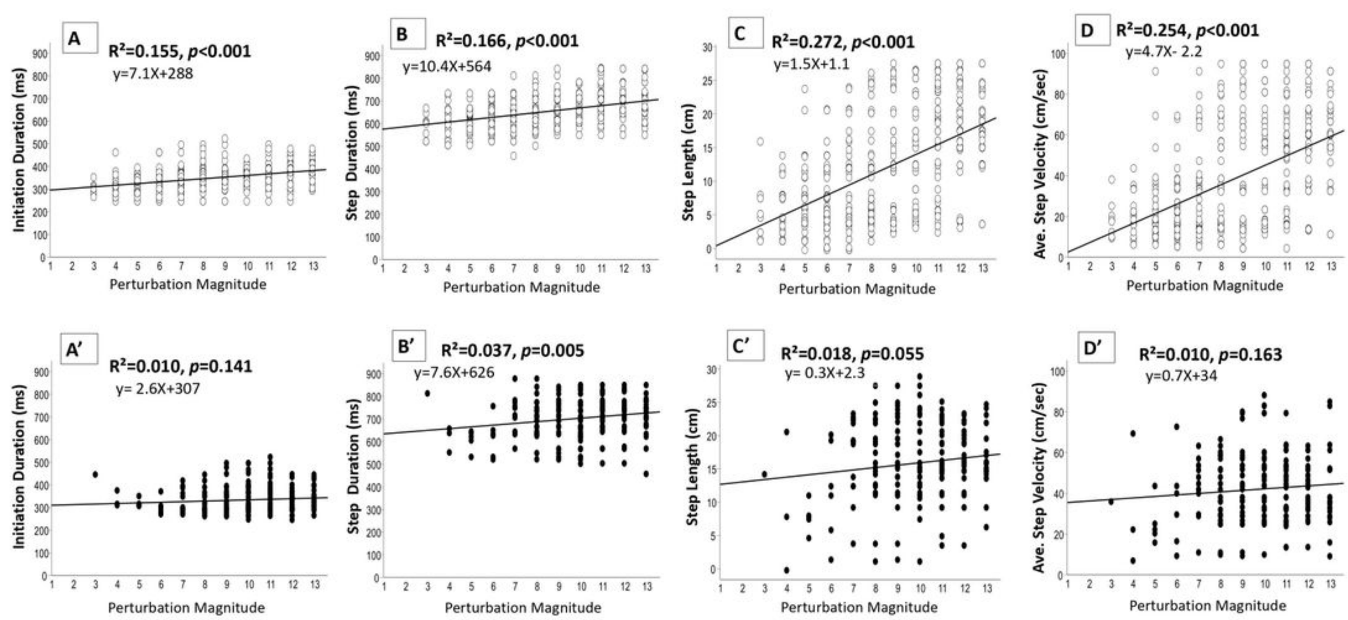

Figure 1

Kinematics of the first recovery step of single-step and multiple-step reactions at increasing perturbation magnitudes. Effect of increasing magnitude on the first recovery step parameters —A–D show results for single-step reactions (white circles), A'–D' show results for multiple-step reactions (black circles). (A) and

(A') represent step initiation durations, (B) and (B') represent step durations, and (C) and (C') step length. Abbreviations: cm = centimeters; ms = milliseconds; sec = seconds

Figure 2:

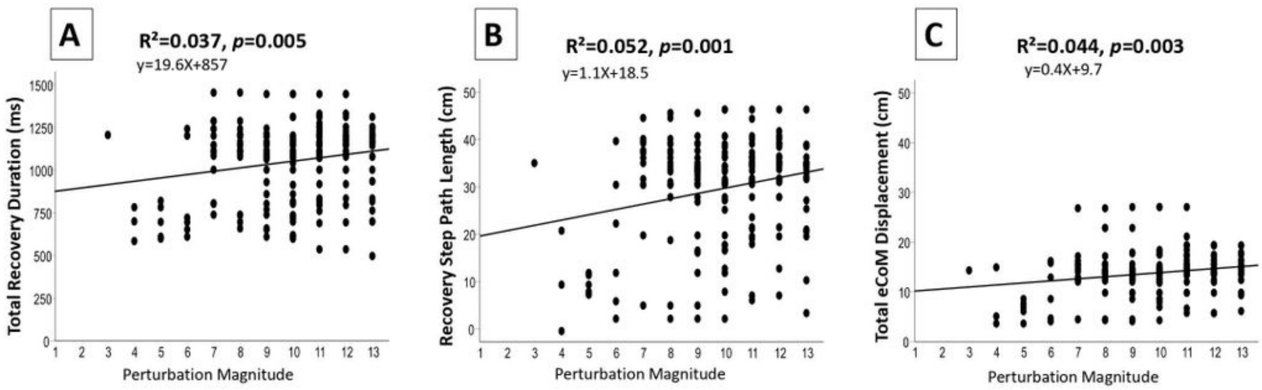

Figure 2

Kinematics of the total recovery step parameters at increasing perturbation magnitudes. Effect of increasing magnitude on the total recovery step parameters —A–C show results for multiple-step reactions (black circles): (A) Total recovery step durations, (B) Total recovery step path length, and (C) Total estimated CoM displacement. Abbreviations: cm = centimeters; ms = milliseconds; sec = seconds

Figure 3:

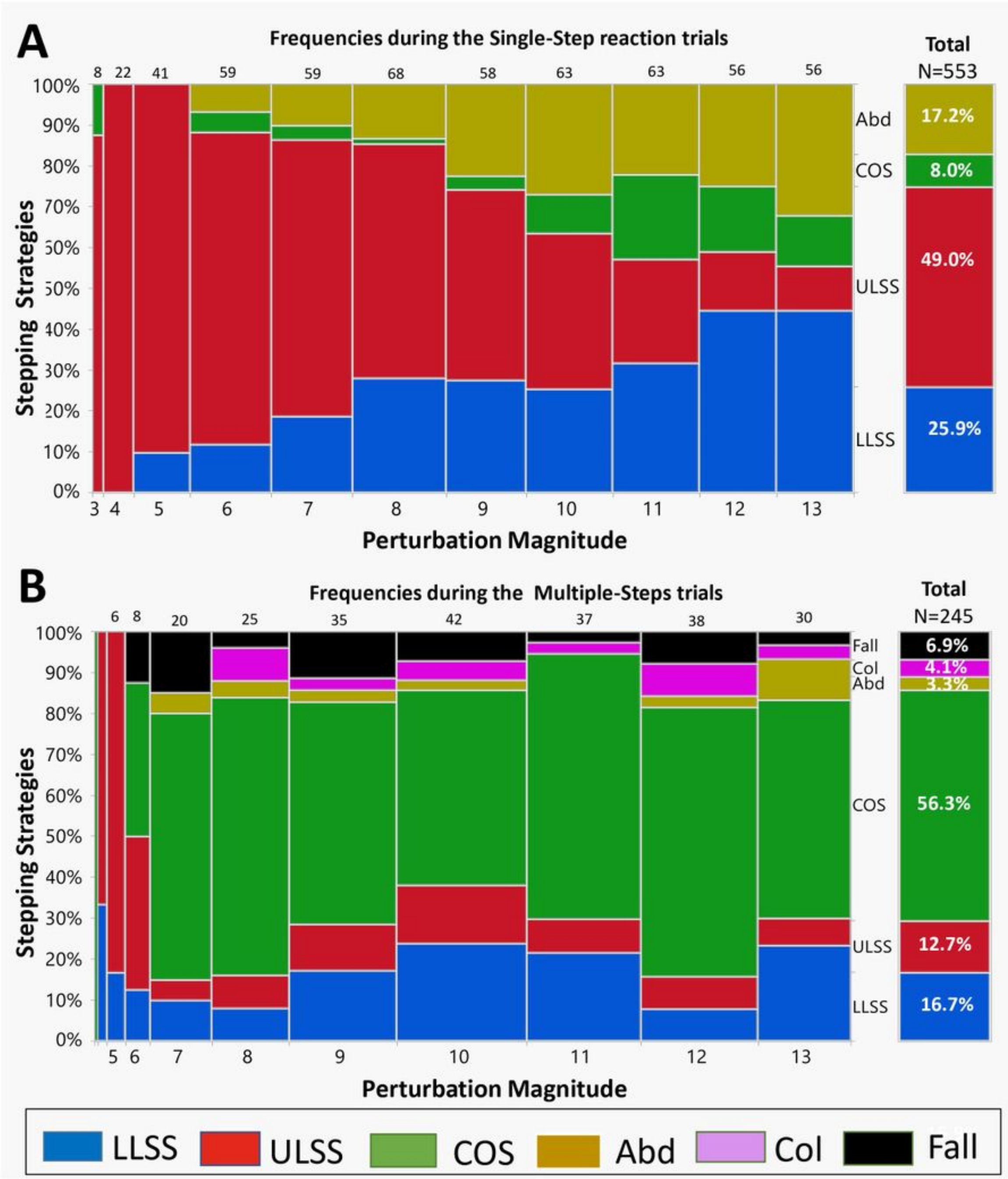

Figure 3

Mosaic plot of the first step strategies in single-step (A) and multiple-step (B) reactions. The mosaic plot is a graphical display of the leg strategy frequencies (Y-axis) by perturbation magnitudes (X-axis) during the two types of reactions. The widths of the boxes are proportional to the percentage of steps performed out of the total stepping reactions [the total number of single-step (553) and multiple-step reactions (245)] at each magnitude presented at the top of each graph. The heights of the boxes are proportional to the percent of the strategies used to recover from balance loss at each perturbation magnitude level. The isolated right columns summarize all the frequencies of the leg strategies at all magnitudes.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- STROBEchecklistv4combined.docx
- supplementaryTable1surfacetranslationdetails.docx