Published in final edited form as:

Gait Posture. 2018 May ; 62: 80–85. doi:10.1016/j.gaitpost.2018.03.011.

Does local dynamic stability during unperturbed walking predict the response to balance perturbations: an examination across age and falls history

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Abstract

Background: Older adults are at an exceptionally high risk of falls, and most falls occur during locomotor activities such as walking. Reduced local dynamic stability in old age is often interpreted to suggest a lessened capacity to respond to more significant balance challenges encountered during walking and future falls risk. However, it remains unclear whether local dynamic stability during normal, unperturbed walking predicts the response to larger external balance disturbances.

Research question: We tested the hypothesis that larger values of local dynamic instability during unperturbed walking would positively correlate with larger changes thereof due to optical flow balance perturbations.

Methods: We used trunk kinematics collected in subjects across a spectrum of walking balance integrity - young adults, older nonfallers, and older fallers - during walking with and without mediolateral optical flow perturbations of four different amplitudes.

Results: We first found evidence that optical flow perturbations of sufficient amplitude appear capable of revealing independent effects of aging and falls history that are not otherwise apparent during normal, unperturbed walking. We also reject our primary hypothesis; a significant negative correlation only in young adults indicated that individuals with more local dynamic instability during normal, unperturbed walking exhibited *smaller* responses to optical flow perturbations. In contrast, most prominently in older fallers, the response to optical flow perturbations appeared independent of their baseline level of dynamic instability.

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Conflict of Interest Disclosure

We have no conflicts of interest to disclose.

Significance: We propose that predicting the response to balance perturbations in older fallers, at least that measured using local dynamic stability, likely requires measuring that response directly.

Keywords

Balance; Elderly; Lyapunov; Stability

INTRODUCTION

Balance control, particularly that during locomotor activities like walking, is negatively affected by aging and disease. Given the tremendous functional consequences of falls, numerous techniques have emerged to quantify balance integrity for diagnostics and prevention. Of these techniques, local dynamic stability (*i.e.*, Lyapunov exponents) has garnered widespread use and significant scientific and clinical interest. For example, older adults (versus young) and people with neurodegenerative disease (versus controls) exhibit reduced local dynamic stability during walking [1, 2]. These reductions are often interpreted to suggest a lessened capacity to respond to more significant balance challenges encountered during walking and future falls risk. However, local dynamic stability quantifies resilience to small, naturally occurring kinematic deviations arising normally during walking [3, 4], and may not reflect resilience to larger external perturbations that could elicit a fall.

Determining the extent to which local dynamic stability during normal, unperturbed walking can predict one's resilience to external balance perturbations may be an especially timely goal for those in our aging population; recent evidence suggests that the rate of injurious falls among older adults is increasing [5]. Detecting a balance disturbance and executing the corrective motor responses that follow depends on integrating reliable sensory feedback [6, 7]. Visual feedback, in particular, involves ~70% of the sensory neurons in the human brain during walking [8], can override other sensory modalities [9, 10], and becomes the sensorimotor locus for balance control in older adults [11, 12]. Perhaps consequently, perturbations of optical flow during walking yield more intense responses in older than in young adults [13, 14]. These perturbations can also elicit age-related differences in local dynamic stability that are not otherwise apparent during unperturbed walking [15]. Hence, optical flow perturbations represent a promising paradigm to test for associations between local dynamic stability normally exhibited during walking and the response to larger, external balance challenges.

Older adults with a history of falls exhibit disproportionate changes in the integrity of balance control compared to non-fallers [16]. Indeed, compared to non-fallers, older fallers walk normally with increased movement variability (though, see [17]) and decreased local dynamic stability – the latter also retrospectively associated with the number of falls in the preceding year [18]. Accordingly, young adults, older non-fallers, and older fallers coalesce to provide a spectrum of walking balance integrity as quantified using local dynamic stability. However, prior work reporting response to optical flow perturbations has thus far: (*i*) excluded that in older adult fallers and (*ii*) focused on group-average comparisons that may confound relations between unperturbed walking and response to balance perturbations.

The purpose of this study was to investigate the extent to which local dynamic stability during normal, unperturbed walking predicts the response to optical flow perturbations. We hypothesized that larger values of local instability during unperturbed walking would positively correlate with larger changes thereof due to optical flow perturbations. We designed our recruitment plan to target a spectrum of walking balance integrity. Specifically, we tested our hypothesis across groups of young adults, older non-fallers, and older adults with a history of falls walking in a virtual environment with and without mediolateral optical flow perturbations. Accordingly, we tested the secondary hypothesis that aging and falls history increase local dynamic instability, particularly in the presence of optical flow perturbations.

MATERIALS AND METHODS

Subjects

Based on previously published results [15], we estimated our sample size to have 80% power to detect ($p < 0.05$): (i) a 21.5% reduction in local dynamic stability in older non-fallers due to small amplitude (20 cm) optical flow perturbations ($n=8$ subjects), and (ii) between-group differences in local dynamic stability between young and older non-fallers walking in the presence of same small amplitude perturbations (*i.e.*, 1.38 ± 0.20 vs. 1.19 ± 0.10 bits·stride⁻¹) ($n=11$ subjects/group). Thus, we recruited 11 young (5 males, 6 females), 11 older adult non-fallers (5 males, 6 females), and 11 older adults self-reporting at least one fall in the last year (4 males, 7 females). Table 1 summarizes their characteristics. Falls counting toward the self-reported total were defined according to the Kellogg International Work Group - unintentionally coming to the ground or some lower level and other than as a consequence of sustaining a violent blow, loss of consciousness, or sudden onset of paralysis [19]. We excluded subjects with BMI ≥ 30 , sedentary lifestyle, orthopedic or neurological condition, or taking medication that causes dizziness. Subjects completed a falls efficacy scale to assess fear of falling (Table 1), and gave written informed consent according to the UNC Chapel Hill IRB.

Protocol and data collection

We reanalyzed young adult data from a previously published study [20]. In that study, young adults walked on an instrumented, dual-belt treadmill (Bertec Corp., Columbus, OH) at $1.25 \text{ m}\cdot\text{s}^{-1}$ - a speed not significantly different from their preferred overground walking speed ($1.29 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$, $p=0.527$). Here, older fallers ($1.03 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$) and non-fallers ($1.19 \pm 0.20 \text{ m}\cdot\text{s}^{-1}$) walked on the same treadmill at their preferred overground speed, calculated from the average of two times taken to traverse the middle 3 m of a 10 m walkway. We note that these speeds differed significantly only between older fallers and young adults ($p=0.007$). All subjects began by walking at their preferred walking speed on the treadmill for 5 minutes to become acclimated to the laboratory environment.

Subjects watched a speed-matched, immersive virtual hallway rear-projected onto a semi-circular screen surrounding the treadmill ($1.45 \text{ m radius} \times 2.54 \text{ m height}$, Fig. 1). To the motion of the virtual hallway, we added continuous mediolateral oscillations of optical flow as a sum of three sine waves (0.125, 0.250, and 0.442 Hz), applied such that the foreground

moved at full amplitude while the end of the hallway remained nearly stationary. These frequencies replicate those in prior studies and fall below those that would elicit discomfort, but enough to provoke instability [21]. In fully-randomized order, subjects walked for 2 min without perturbations and for 2 min each exposed to one of three amplitude continuous optical flow perturbations per condition (*i.e.*, 20, 35, and 50 cm). To enhance perturbation complexity that would be difficult for subjects to anticipate, the full amplitude was applied at 0.250 Hz, and half that amplitude was applied at 0.125 Hz and 0.442 Hz. All subjects wore a harness secured via an overhead support system. A 14-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) operating at 100 Hz recorded the 3D trajectories of markers placed on subjects' heels, posterior sacrum, and C7 vertebrae (*i.e.*, a surrogate for upper torso motion used in prior studies that would be insensitive to head turns [22]).

Data analysis

Consistent with prior studies [1], we filtered marker trajectories using a 4th-order zero-lag low-pass digital Butterworth filter with cutoff frequency of 8 Hz, which preserved more than 99% of the power in the raw data (see supplementary material for effects of cutoff frequency). We then quantified **local dynamic stability by estimating** the maximum exponential rates of divergence (*i.e.*, λ , bits·stride⁻¹) derived from 3D C7 marker velocity time series [4, 23] (Eqn. 1). We used velocity, rather than position, time series to reduce signal non stationarities that can compromise local dynamic stability estimates [1]. We used the following to construct the state space, $S(t)$,

$$\mathbf{q}(t) = (\dot{x}, \dot{y}, \dot{z}) \quad (1)$$

$$S(t) = [\mathbf{q}(t), \mathbf{q}(t + \tau), \mathbf{q}(t + 2\tau), \dots, \mathbf{q}(t + (d_E - 1)\tau)] \quad (2)$$

where, $\dot{x}$, $\dot{y}$ and $\dot{z}$ correspond to C7 velocity components in the anterior-posterior, mediolateral, and vertical directions, respectively. We then computed maximum rates of divergence of initially neighboring trajectories from $S(t)$ using prescribed values for the embedding dimension (d_E) and time delay (τ) (Eqn. 2) [23]. We determined the embedding dimension ($d_E=4$) using a false nearest neighbor algorithm and a 10% criterion [24, 25]. By convention, we prescribed the time delay (τ) as one quarter of subjects' average stride time for each condition [26], calculated as the average duration between successive heel strikes [27]. We time normalized the divergence curves to account for differences in stride period and then calculated each subject's maximum short-term λ_S (0 to 1 stride) and long-term λ_L (4 to 10 strides) divergence exponents for each condition. Here, larger positive values of λ signify larger local dynamic instability. Finally, we determine the sensitivity of these divergence exponents to the selection of embedding dimension (d_E) and time delay (τ), using parallel computing to repeat all calculations while sweeping d_E from $\frac{1}{8}$ to $\frac{1}{2}$ of subjects' average stride time for each experimental condition (See supplementary material).

Statistical analysis

A mixed, 2-way factorial ANOVA determined the significance and effect size (η^2) of main effects of or interactions between group (young, older non-fallers, and old fallers) and optical flow perturbations (unperturbed, 20, 35, and 50 cm) using an alpha level of 0.05. When a significant main effect or interaction was found, *post-hoc* least significant difference (LSD) pairwise comparisons examined the effect of group within each condition. We also used an analysis of covariance (ANCOVA) to adjust the means of the dependent variables (λ_S and λ_L) for between-group differences in treadmill speed as a covariate [28]. Finally, for groups exhibiting a significant condition main effect, linear regression estimated the relation between local dynamic stability during unperturbed walking ($\lambda_{\text{unperturbed}}$) and the average change thereof in response to the three perturbation amplitudes (*i.e.*, $\bar{\lambda}_{\text{perturbed}} - \lambda_{\text{unperturbed}}$). To further examine these correlations, linear regression then estimated the relation between local dynamic stability during unperturbed walking ($\lambda_{\text{unperturbed}}$) and the average of that when walking with perturbations ($\bar{\lambda}_{\text{perturbed}}$).

RESULTS

Aging and falls history effects on dynamic instability

We observed a significant main effect of group on short-term (λ_S , $p=0.004$, Fig. 2A), but not long-term (λ_L , $p=0.540$, Fig. 2B) local dynamic instability, even after controlling for differences in walking speed (ANCOVA, $p=0.018$ for λ_S and $p=0.603$ for λ_L , respectively). Pairwise comparisons revealed that this effect was governed primarily by age (non-fallers *vs.* young, $p=0.033$), independent of falls history (non-fallers *vs.* fallers, $p=0.120$). However, we found that neither age nor falls history significantly affected dynamic instability during unperturbed walking (main effect, ANOVA: $p=0.053$, ANCOVA: $p=0.172$, Fig. 2A). Compared to unperturbed walking, optical flow perturbations significantly increased short-term (main effect, $p<0.001$, Fig. 2A), but not long-term (main effect, $p=0.057$, Fig. 2B) local dynamic instability – an effect observed for all subject groups (young: $p<0.001$, non-fallers: $p=0.009$, fallers: $p<0.001$, Fig. 2A).

Perturbations revealed between-group differences in local dynamic instability that were not otherwise apparent during unperturbed walking. Age alone increased local dynamic instability during walking only for the 35 cm amplitude perturbation (non-fallers *vs.* young, $p=0.035$); however, this effect failed to reach significance after controlling for walking speed (ANCOVA: $p=0.067$) (Fig. 2A). In contrast, whether or not we controlled for walking speed, fallers exhibited larger local dynamic instability than young adults for all three perturbation amplitudes (fallers *vs.* young: $p=0.009$ for 20 cm, $p=0.002$ for 35 cm, $p<0.001$ for 50 cm, Fig. 2A). We observed no difference in local dynamic instability between fallers and non-fallers for the two smallest amplitude perturbations (20 cm: $p=0.445$, 35 cm: $p=0.477$). However, although not statistically significant, fallers tended to have larger local dynamic instability than non-fallers at the largest amplitude ($p=0.059$).

Predicting the response to perturbations

Across all subjects, we found a significant but modest negative correlation between short-term local instability during unperturbed walking and changes thereof due to optical flow perturbations ($p=0.013$, $R^2=0.18$, Fig. 3A). However, this relation differed across individual groups. Young adults had the only significant and by far the strongest and steepest, negative correlation between local instability during unperturbed walking and response to perturbations ($R^2=0.68$, $p=0.002$, Fig. 3B). Compared to young adults, this relation was similarly steep but much less well correlated in older non-fallers ($R^2=0.23$, $p=0.133$, Fig. 3C). Finally, older fallers exhibited by far the most shallow regression between short-term local instability during unperturbed walking and changes thereof due to optical flow perturbations ($R^2=0.26$, $p=0.108$, Fig. 3D). Indeed, the relation between local dynamic instability during perturbed and unperturbed walking reached significance and approximated the line of unit only for older fallers (Fig. 3H), indicating a uniform response across this cohort.

DISCUSSION

Determining the extent to which local dynamic stability during normal, unperturbed walking can predict one's resilience to external balance perturbations is an especially timely goal for those in our rapidly aging population. We tested the hypothesis that local dynamic stability during normal, unperturbed walking could predict the response to optical flow perturbations. Consistent with our prior work, we found that: (i) each group (*i.e.*, young, older non-fallers, older fallers) was acutely susceptible to perturbed optical flow, and (ii) perturbations revealed age-related differences in local dynamic stability that were not apparent during unperturbed walking. The present study makes two additional contributions. First, although modest, our data suggest that older adults with a history of at least one fall have a more pervasive susceptibility to optical flow perturbations than older non-fallers during walking. Second, in surprising contrast to our hypothesis, a significant negative correlation across our study cohort indicated that individuals with higher local dynamic instability during unperturbed walking exhibited *smaller* responses to optical flow perturbations. Upon more careful analysis, we revealed that this association held only for young adults and that we have the least ability to predict the response to balance perturbations among older fallers. Our findings have important implications for the use of balance perturbations in detecting falls risk and, more broadly, our interpretation of local dynamic stability in quantifying the integrity of walking balance control.

Aging increases the reliance on vision for motor planning and execution [10]. Accordingly, we continue to find evidence that older adults are more susceptible than young adults to optical flow perturbations designed to elicit the perception of lateral imbalance during walking. Local dynamic stability estimates one's resilience to small, naturally occurring deviations that can arise from the internal control system and the external environment [3]. Perhaps governed by visual dependence [10], we found here that only during perturbed walking was dynamic stability significantly different between young adults and older nonfallers. Other contributing factors may include age-associated declines in sensorimotor function or cognition and executive function [29]. Also consistent with prior studies [1], this

greater susceptibility in older adults held only for short-term divergence exponents; long-term exponents were not different between groups and tended to improve with perturbations. As other authors have described, this is consistent with expectations for treadmill walking, in which movement patterns must remain loosely bounded. Indeed, based on model predictions, Bruijn et al. (2012) concluded that long-term exponents provide, at best, only limited insight into stability during human walking [30].

In their seminal paper, Lord and Webster (1990) revealed that a dependence on visual feedback was much more pronounced in older adults with a history of falls compared to nonfallers [31]. Moreover, those authors proposed that visual stimuli, or changes thereof, may play a role in postural instability and falls in the elderly. In contrast to some prior work, we found no effect of falls history, independent of age, on short-term local dynamic stability during unperturbed walking. This may be explained by our inclusion criteria, for which older fallers needed only self-report a single fall in the last year. We also found that smaller amplitude perturbations elicited no difference in local dynamic stability between older fallers and non-fallers. However, on the cusp of statistical significance compared to non-fallers, our results do allude to an increased susceptibility to larger amplitude optical flow perturbations in older adults with a history of at least one fall. While this would be consistent with the results of Lord and Webster (1990), we also note several other explanations. Beyond those changes due to aging, older fallers may exhibit accelerated declines in sensorimotor and cognitive acuity [32, 33]. Older fallers also have an increased fear of consecutive falls [34], which may yield changes in locomotor behavior arising from their assessment of risk in the presence of perturbations. Whatever the mechanism, our results suggest that the clinical utility of optical flow perturbations in detecting falls risk may depend on their evidenced-based design (*e.g.*, amplitude, frequency).

We hypothesized that larger values of local dynamic instability during normal, unperturbed walking would positively correlate with larger changes thereof due to perturbations. Based on our results, we must altogether reject this hypothesis; only in young adults did we find a significant correlation, which described an unexpected relation between normal walking stability and response to balance perturbations. Specifically, young adults presenting with higher local dynamic instability during unperturbed walking were those that exhibited the *smallest* response to optical flow perturbations and vice versa. We previously acknowledged the possibility that local dynamic stability may not reflect the response to larger, external balance challenges [20]. One interpretation of our current findings is that young adults may self-regulate their response to balance perturbations. Although speculative, this could, in theory, arise from a self-perception of risk guided by their baseline level of dynamic instability. Here, an individual with less dynamic instability may permit larger responses to the same amplitude balance perturbation.

In contrast to our hypothesis, we found no significant relation between dynamic instability during unperturbed walking and changes thereof due to optical flow perturbations in older adults. Instead, at least among older adult fallers, we found that dynamic instability during unperturbed walking was strongly and positively correlated with that during perturbed walking. The extent to which this relation nearly reproduced the line of unity suggests that older adult fallers' response to optical flow perturbations was relatively independent of their

baseline level of dynamic instability. Assuming that the interpretation of our young adult data holds, these findings would imply that older fallers no longer self-regulate their response to balance perturbations. Thus, while larger amplitude optical flow perturbations appear to reveal changes to dynamic instability unique to older adults with a history of falls, we have the least ability to predict an individual's response to perturbations among older adult fallers. Accordingly, understanding the response to balance perturbations, especially among older fallers, may require measuring that response directly rather than relying on measures collected during normal, unperturbed walking – a major takeaway from this study.

We have described the limitations of our optical flow paradigm [13, 20]. However, there are additional limitations specific to this study that should be considered when interpreting our results. First, our inclusion criteria required that older adult fallers self-report only a single relatively recent fall. It is unclear if our results would hold for those with a more pervasive history of recurrent falls. Second, there are many other metrics of walking balance, including variability, margins of stability, and Floquet multipliers. Although we opted to focus on maximum divergence (*i.e.*, Lyapunov) exponents, our results should inspire future studies to examine the ability of other measures derived from unperturbed walking to predict the response to external balance challenges. Third, although designed a priori, we recruited a relatively small number of subjects for each cohort. However, with effect sizes reported for all primary comparisons, our results allude to between-group differences and perturbation effects that should help generate hypotheses and inform the design of future testing in a larger cohort. Fourth, although our older adult fallers walked slower than young adults, accounting for this difference did not affect our statistical outcomes nor interpretations. Nevertheless, we cannot definitively exclude the possibility that our results would differ had we prescribed the same walking speed for all subjects. Prior studies [35, 36], including a recent walking study [37], also show that people can and do adapt to optical flow perturbations, perhaps through a process of multisensory reweighting. Those studies in standing further support that age and falls history can slow this reweighting process compared to young adults [38]. This potential for adaptation was outside the scope of the present design, which included relatively short walking trials and thus studied the more acute response to perturbations. Thus, we cannot say whether our subject cohorts adapted differently to perturbations during each walking trial or if and how this may have influenced our findings. Fifth, we prescribed the same perturbations for all subjects, and speed-matched the virtual hallway to each subjects' preferred speed; however, we acknowledge that immersion and the visual perception of self-motion may differ with individual preferences. We also disclose that time series analyses can be sensitive to differences in variability between groups and that we did not in this study perform more sophisticated surrogate/phase randomization analyses that may rule out those affects. Finally, our conclusions may be specific to optical flow perturbations, and may not reflect the response to external mechanical perturbations (*e.g.*, surface translations).

We sought to investigate the extent to which local dynamic stability during normal, unperturbed walking predicts the response to optical flow perturbations. This relation was more complex than anticipated, and differed with aging and falls history. In young adults, we discovered evidence of a mechanism by which individuals may actively regulate their response to perturbations according to their baseline level of dynamic instability - a

mechanism that seems absent in older adults. Especially in older fallers, the response to perturbations appeared independent of one's baseline level of dynamic instability. Accordingly, predicting the response to balance perturbations in older fallers likely requires measuring that response directly. Finally, optical flow perturbations appear capable of revealing effects of aging and falls history that are not apparent during unperturbed walking. Our findings may have practical implications for those interested in identifying falls risk, developing technologies designed to mitigate that risk, or evaluating rehabilitative programs to improve balance.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

We gratefully acknowledge Ms. Jessica Thompson and Ms. Heather Stokes for their help with data collection. This study was supported in part by the North Carolina State University Abrams scholarship program and by grants from the National Center for Advancing Translational Sciences (UL1TR001111), UNC/NC State CLEAR core, and the National Institutes of Health (R56AG054797).

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Research Highlights

- Correlated response to perturbations using measurements from unperturbed walking
- Tested the independent effects of age and falls history on local dynamic stability
- Perturbations revealed age/falls history effects that were not otherwise apparent
- Young adults with more local instability have smaller responses to perturbations
- Older fallers' response to perturbations appears independent of baseline instability

Figure 1:

Subjects walked on a treadmill while watching an immersive, speed matched virtual hallway with continuous optical flow perturbations of different amplitudes, *e.g.*, unperturbed, 20 cm, 35 cm, and 50 cm.

Figure 2:

Mean $\pm$ standard deviation effects of group (*e.g.*, young adults, non-fallers, and fallers) and optical flow perturbation (unperturbed, 20 cm, 35 cm, and 50 cm) on (A) short-term (λ_S) and (B) long-term (λ_L) local dynamic instability calculated from kinematic trajectories of the C7 vertebrae. Asterisks (*) indicate a significant ($p < 0.05$) main effect of group for a given condition of optical flow perturbation. The effect sizes in panel A: $\eta^2_{\text{group}} = 0.312$, $\eta^2_{\text{perturbation}} = 0.580$; The effect sizes in panel B: $\eta^2_{\text{group}} = 0.040$, $\eta^2_{\text{perturbation}} = 0.080$.

Figure 3:

The top row shows correlations between short-term local dynamic instability during unperturbed walking ($\lambda_{\text{unperturbed}}$) and the average change thereof in response to optical flow perturbations ($\Delta\lambda = \lambda_{\text{perturbed}} - \lambda_{\text{unperturbed}}$) for (A) all groups combined, regression power 0.746, (B) young adults, regression power 0.990, (C) older non-fallers, regression power 0.371, and (D) older adult fallers, regression power 0.423. The bottom row shows correlations between $\lambda_{\text{unperturbed}}$ and the average in response to optical flow perturbations ($\lambda_{\text{perturbed}}$) for (E) all groups combined, regression power 0.845, (F) young adults, regression power 0.061, (G) older non-fallers, regression power 0.067, (H) and older adult fallers, regression power 0.937. Circles are young adults, squares are older non-fallers, and triangles are older adult fallers. The black dashed line represents the best fit least-square linear regression and the solid gray line has a slope of zero (top row) or one (bottom row) indicating, in both, a response to perturbations that is independent of subjects' baseline stability. The regression power in each subplot is based on $1 - \beta$, and $\alpha = 0.05$.

Table 1

Subject characteristics.

	Young (A)	Non-fallers (B)	Fallers (C)	Main Effect
Age (yrs)	24.8 ± 4.8	75.3 ± 5.4 ^A	78.3 ± 7.6 ^A	$P < 0.001$
Mass (kg)	67.2 ± 8.8	73.4 ± 16.1	69.3 ± 14.0	$P = 0.553$
Height (m)	1.72 ± 0.09	1.75 ± 0.10	1.66 ± 0.12	$P = 0.159$
Falls Efficacy	–	10.3 ± 0.6	12.5 ± 3.0 ^B	$P = 0.028$

Mean ± standard deviation.