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Short Communication:

Locomotor stability and adaptation during perturbed walking across the adult female lifespan

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Abstract

The aim of this work was to examine locomotor stability and adaptation across the adult female lifespan during perturbed walking on the treadmill. 11 young, 11 middle and 14 older-aged female adults (mean and SD: 25.5(2.1), 50.6(6.4) and 69.0(4.7) years old respectively) walked on a treadmill. We applied a sustained perturbation to the swing phase of the right leg for 18 consecutive gait cycles, followed by a step with the resistance unexpectedly removed, via an ankle strap connected to a break-and-release system. The margin of stability (MoS) at foot touchdown was calculated as the difference between the anterior boundary of the base of support (BoS) and extrapolated center of mass. Older participants showed lower MoS adaptation magnitude in the early adaptation phase (steps 1-3) compared to the young and middle-aged groups. However, in the late adaptation phase (steps 16-18) there were no significant differences in adaptation magnitude between the three age groups. After removing the resistance, all three age groups showed similar aftereffects (i.e. increased BoS). The current results suggest that in old age, the ability to recalibrate locomotion to control stability is preserved, but the rate of adaptive improvement in locomotor stability is diminished.

Introduction

Reducing falls in the elderly is vital for public health, due to consequences such as fractures, functional decline and death (Terroso et al., 2014). Older adults fall most often during ambulation, frequently due to tripping or slipping (Talbot et al., 2005). Reactive and predictive adjustments of gait contribute to locomotor stability (state of the center of mass (CoM) in relation to the base of support (BoS)) and decrease the risk of falling when facing a challenging walking environment (Bierbaum et al., 2010; Bierbaum et al., 2011). One such adjustment is rapid stepping, which is diminished in old age (Maki and McIlroy, 2006). Step length and time following release from a forward lean indeed predict older adults' maximum recoverable forward lean angle (Graham et al., 2015), which predicts future falls (Carty et al., 2015).

Improving compensatory stepping adjustments may help in preventing falls (Grabiner et al., 2014). In older adults, experiencing laboratory-induced gait perturbations has led to improved recovery responses to various mechanical perturbations (Bhatt et al., 2012; Bierbaum et al., 2010; Bierbaum et al., 2011; Pai et al., 2010; Pai et al., 2014b). More importantly, perturbation training may reduce falls by up to 50% in the following year (Pai et al., 2014a; Rosenblatt et al., 2013). However, it remains partly unclear how locomotion adapts to control stability in response to perturbations, and how this ability declines across the adult lifespan. Determining how locomotor stability and adaptation are affected across the female lifespan is of particular importance, as locomotor stability declines, and falls increase in middle age in women (Süptitz et al., 2013; Talbot et al., 2005). Women over 45 have an increased susceptibility to bone fractures (Donaldson et al., 1990), and experience more fall-related injuries (Talbot et al., 2005) and hip fractures (Parkkari et al., 1999) than men.

Bruijn et al. (2012) found that older adults show diminished step length adaptation in response to a split-belt walking paradigm (one belt at 1m/s, the other at 0.5m/s) compared with younger adults. Bierbaum et al. (2010), however, found that older adults are capable of adapting their dynamic stability to a similar or greater magnitude as young adults to surface change perturbations. Additionally, Pai et al. (2010) showed that older adults are capable of predictive and reactive adaptations to slip perturbations. In general however, there is a lack of studies on aging and locomotor stability and adaptation and importantly, no study has analyzed how the adaptability of locomotion to perturbations is affected across the adult lifespan using a cross sectional design. This study aimed to examine locomotor stability and adaptation in young, middle and older-aged adults in response to a sustained resistance perturbation during walking, in order to test the hypothesis that older adults remain capable of adapting their locomotion to external gait perturbations in order to maintain stability, but not to the same extent as young and middle-aged adults.

Methods

Eleven young (mean and SD: 25.5(2.1) years), 11 middle-aged (50.6(6.4) years) and 14 older (69.0(4.7) years) healthy women, with no known musculoskeletal or neurological deficits, participated in this study. The height and body mass for each group were 166.9(4.3)cm and 62.7(6.8)kg for the young, 168.2(4.8)cm and 66.4(7.9)kg for the middle-aged, and 161.2(5.0)cm and 67.3(4.7)kg for the older adults respectively. Participants walked at 1.4m/s on a treadmill (pulsar 4.0, h/p/cosmos; Nussdorf-Traunstein, Germany) to standardize the walking speed and perturbation. One treadmill walking familiarization session took place four to seven days before measurements. Participants wore a safety harness connected to an overhead frame during the measurements. The procedures were explained to the participants prior to obtaining informed consent in accordance with the Declaration of Helsinki. The study was approved by the German Sport University Cologne ethical board.

The gait perturbation was applied using a custom built brake-and-release system described previously (McCrum et al., 2014; Süptitz et al., 2013) which applies and removes 2.1kg of resistance to the leg via an ankle strap and Teflon cable, controlled via an electronically driven magnet system. Resistance is turned on during the right leg stance phase and removed following right foot touchdown, so that the entire swing phase is affected. The measurement periods included familiarization, baseline, single perturbation, washout, sustained perturbation and post-perturbation. Familiarization consisted of ten minutes walking at 1.4m/s. The ankle strap was then attached to the right leg and participants walked for a further four minutes. A baseline measurement (non-perturbed walking; approximately 20 seconds) was recorded at the end of this period. Six consecutive steps were used to determine a baseline for the assessed parameters. The resistance was then applied for one step and immediately removed. Following a two to three minute washout period of non-perturbed walking, the resistance was again applied, this time left on for 18 consecutive steps of the right leg, followed by a final step of the right leg with the resistance removed (post-perturbation), in order to examine aftereffects. Aftereffects were analyzed using the BoS, as recalibrations were expected to be most noticeable in this variable. Participants were not warned about the onset or removal of the perturbation, but were informed that a resistance would be applied at some point during walking.

Our method to assess gait stability on the treadmill has been described in previous studies (McCrum et al., 2014; Süptitz et al., 2012; Süptitz et al., 2013), and a detailed description is provided in the appendix (see Supplementary Material). Briefly, a full kinematic model was tracked using 26 markers and an eight camera (120 Hz) Vicon Nexus motion capture system (Vicon Motion Systems, Oxford, UK). The anteroposterior margins of stability (MoS) were calculated at foot touchdown (determined using tibia accelerometer data (ADXL250; Analog Devices, Norwood, MA, USA)) as the difference between the anterior boundary of the BoS (anteroposterior component of the toe projection to the ground) and the extrapolated CoM as defined by Hof et al. (2005).

The parameters of interest were MoS at baseline, at touchdown of the perturbed step during the single perturbation period and of the first six and last five steps during the sustained perturbation period. This method was used due to recording limitations of the motion capture system, which could not record all 18 stride cycles. In order to examine locomotor adaptation, we calculated the MoS adaptation magnitude in a similar manner to Bierbaum et al. (2011) for the early and late adaptation phases of the sustained perturbation period as follows:

$$\text{Adaptation Magnitude} = \left(1 - \frac{MoS_{AdaptPeriod} - MoS_{Base}}{MoS_{Single} - MoS_{Base}}\right) \times 100$$

where $MoS_{AdaptPeriod}$ is either the mean MoS of the first or last three perturbed steps (early or late adaptation period), MoS_{Single} is the MoS at touchdown of the perturbed step during the single perturbation period, and MoS_{Base} is baseline MoS. Finally, in order to examine aftereffects, we compared the BoS during baseline with the step after the unexpected removal of the resistance.

A two-way repeated measures ANOVA with age and step (baseline, single perturbation period step, and the first six and last five steps of the sustained perturbation period) as factors was used to examine age and step related differences in the MoS. Differences in adaptation magnitude were examined using a two-way repeated measures ANOVA with age and adaptation phase (early and late) as factors. To assess potential aftereffects in the BoS, a two-way repeated measures ANOVA with age group and task period (base and post-perturbation) as factors was conducted. Duncan's Tests were applied for pairwise comparisons. The significance level was $\alpha=0.05$. Results are presented as mean and standard error.

Results

A significant age by step interaction was found for the MoS ($p < 0.05$) indicating that the effect of age on the MoS was step specific (Fig. 1). Post-hoc tests revealed no significant differences between groups during baseline. During the single perturbation period, all groups demonstrated significantly lower MoS in comparison to baseline ($p < 0.05$) with no between age group differences. Significantly lower MoS compared to baseline was found for all groups for all steps in the sustained perturbation period ($p < 0.05$). The older age group demonstrated significantly lower MoS for the first six steps of the sustained perturbation period ($p < 0.05$) compared with the younger groups, however there were no significant differences in MoS between the age groups for the last five steps (steps 14-18; $p > 0.05$).

Insert Fig.1

Regarding the adaptation magnitude, the ANOVA revealed a significant age by adaptation phase interaction ($p < 0.05$; Fig. 2). Post-hoc tests revealed significant differences between age groups only during the early adaptation phase, with the older group showing a significantly lower adaptation magnitude ($p < 0.05$; Fig. 2). At touchdown of the final measured step with the resistance unexpectedly removed, significant aftereffects were seen in all groups, with a significantly increased BoS ($p < 0.05$; Fig. 3) compared to baseline, with no significant differences found between the age groups ($p > 0.05$; Fig. 3).

Insert Figs. 2 and 3

Discussion

We aimed to examine locomotor stability and adaptation in response to a sustained perturbation in young, middle and older-aged female adults. Our hypothesis, that older adults remain capable of adapting to external gait perturbations, but not to the same extent as younger adults, was partly supported, as the older adults demonstrated a similar adaptation magnitude of the MoS to the young and middle-aged adults by the end of the sustained perturbation period. However, in the first three steps of the sustained perturbation period, the older adults showed significantly lower MoS adaptation magnitude compared to the young and middle-aged groups, suggesting that while they could adapt to a similar magnitude, this occurred slower than in the younger groups. This declined rate of adaptation was not present in middle-aged adults.

The MoS adaptation magnitude was significantly decreased in the early adaptation phase for the older group compared to the other groups. This indicates that adaptations made following the initial single perturbation were not as substantial in the older group as in the other groups, indicating a higher risk for older adults in situations with perturbations in quick succession (e.g. uneven terrain). That being said, all age groups demonstrated significant improvements in MoS adaptation magnitude by the late adaptation phase, suggesting that the locomotor adaptability was not diminished in any age group. Similar results were seen in the BoS, showing that older adults struggled to cope with the early perturbations (see Fig. S1 in the Supplementary Material).

Our analysis of the aftereffects in the BoS support the role of a recalibration of locomotion in our participants, as all subject groups showed a significant increase in the BoS after the resistance was removed (Fig. 3). These findings suggest that the recalibration of motor commands may not be significantly affected by aging, although adaptation may occur more quickly in younger than in older adults. The aftereffects indicate either, that older adults are able to retain adaptations after only a few perturbations, or that they demonstrate perseverance after resistance removal. However, to specifically investigate this, many more perturbations would be required, which due to the task's physical demand, was not considered feasible.

While Bruijn et al. (2012) reported deficient step length adaptation in older adults, their walking speed was substantially slower than our 1.4m/s, which may not have required such significant adaptation rates or magnitudes to continue safe forward progression of gait. An additional consideration is the range of different perturbations used across studies, as these could have different effects on the magnitude of adaptations required to maintain stability. A final consideration is that we analyzed three age cohorts, and did not longitudinally follow participants as they grew older, and therefore, our conclusions should be interpreted with this in mind.

In conclusion, our results provide evidence that with aging, the ability to recalibrate locomotion to control stability is preserved. However, a deficient rate of locomotor adaptation can be seen in old age, which may have implications for training interventions and falls prevention.

Conflict of Interest Statement

The authors declare no conflicts of interest.

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Figure Legends

Fig. 1. Margin of stability (MoS) analysis. MoS at foot touchdown (mean and SE) during non-perturbed walking (Base: average of 6 consecutive steps) and during the single and sustained perturbation periods for 11 young, 11 middle-aged and 14 older female adults while walking on the treadmill at 1.4 m/s. All single and sustained perturbation period values were significantly lower than baseline for all groups ($p < 0.05$).

*: Statistically significant difference between the older group and the young and middle-aged groups with no differences between the young and middle-aged groups ($p < 0.05$).

Fig. 2. Adaptation magnitude in MoS in the early and late adaptation phases. The adaptation magnitude for all groups in the early (first three steps) and late (last three steps) adaptation phases in MoS in reference to the single perturbation period.

1 and 2: Statistically significant difference during the early adaptation period to the young and middle-aged groups respectively ($p < 0.05$).

*: Statistically significant difference to the early adaptation period for all groups ($p < 0.05$).

Fig. 3. Aftereffects in the BoS. The BoS for all age groups during non-perturbed walking (Base) and in the first step after the resistance was unexpectedly removed (Post-Pert).

*: Statistically significant difference in the BoS between Post-Pert and Base for all groups ($p < 0.05$).

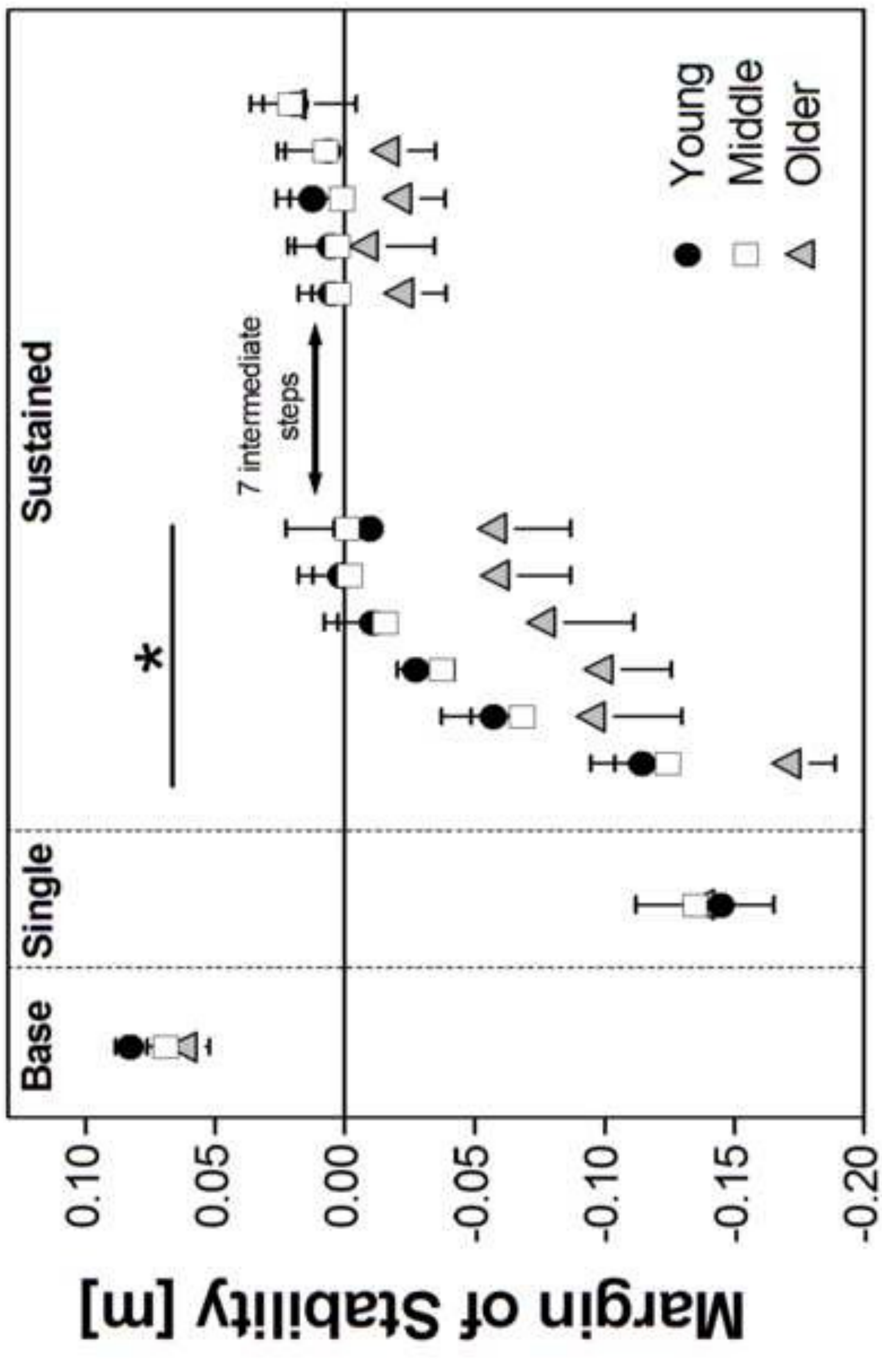
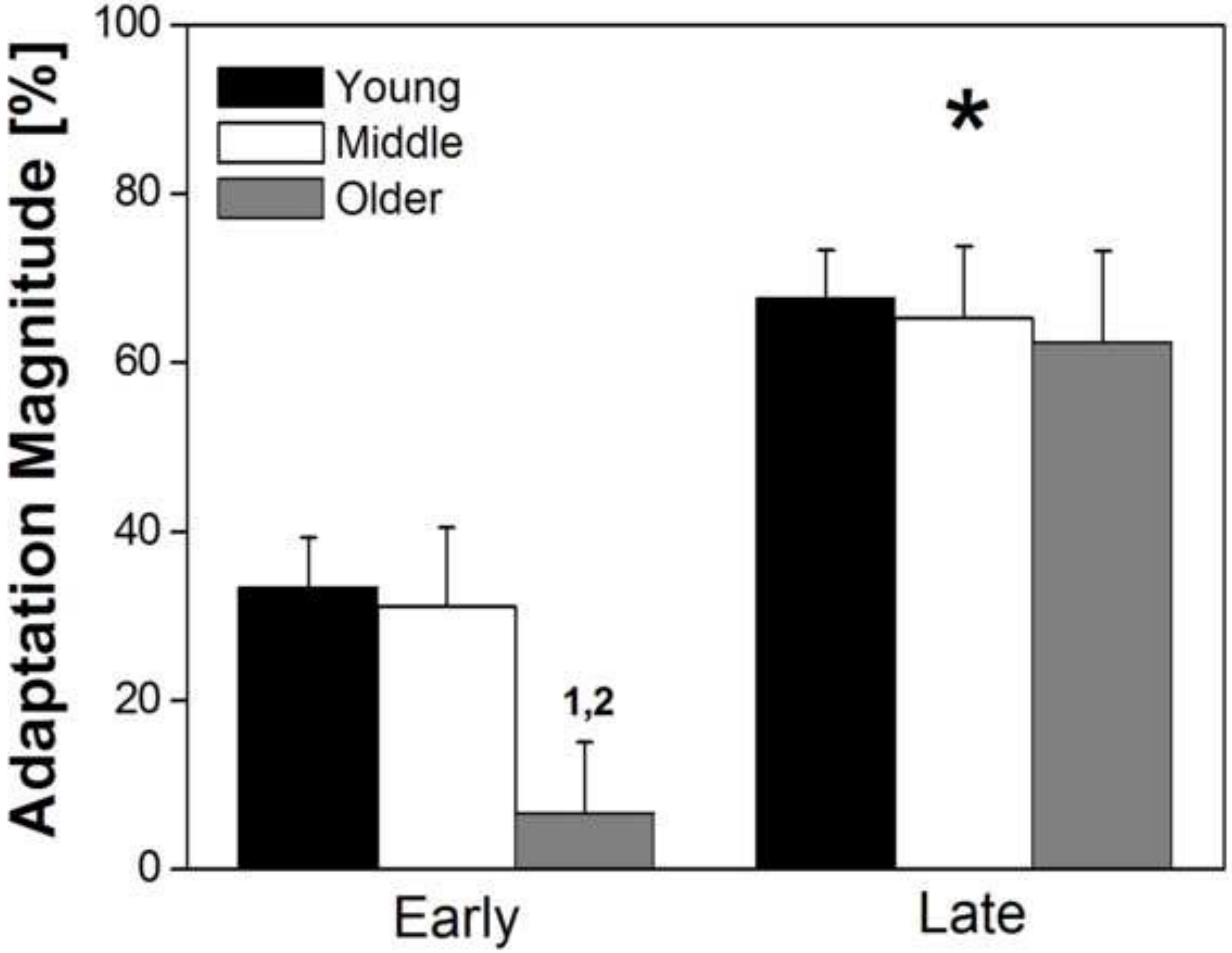

Margin of Stability [m]
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
Base
Single
Sustained
*
7 intermediate steps
Young
Middle
Older

Figure 1

Figure 2


Adaptation Magnitude [%]
100
80
60
40
20
0
Young
Middle
Older
*
1,2
Early
Late

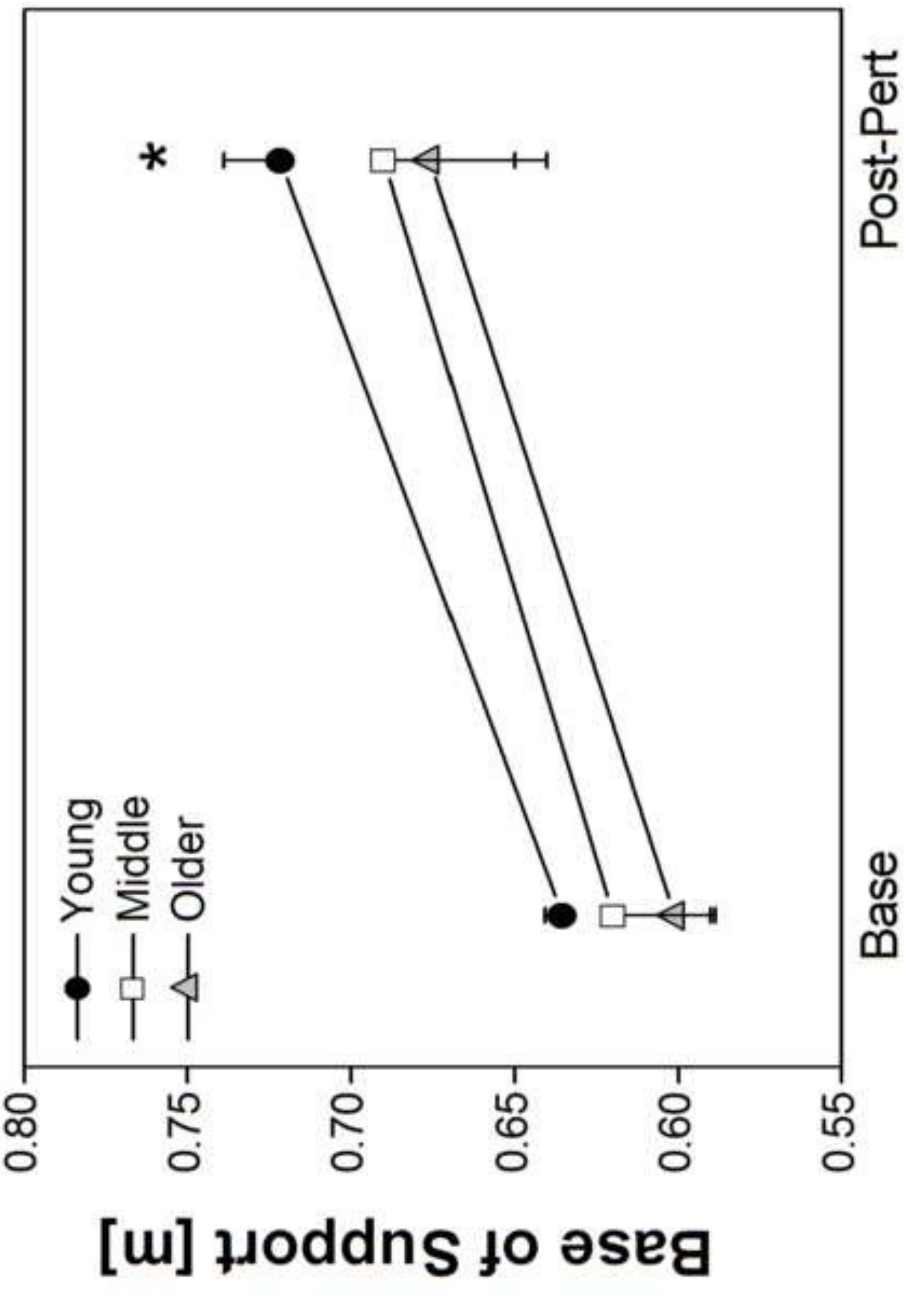

Base of Support [m]
0.80
0.75
0.70
0.65
0.60
0.55
Young
Middle
Older
*
Base
Post-Pert

Figure 3