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## Aging effects of motor prediction on protective balance and startle responses to sudden drop perturbations

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## ABSTRACT

This pilot study investigated the effect of age on the ability of motor prediction during self-triggered drop perturbations (SLF) to modulate startle-like first trial response (FTR) magnitude during externally-triggered (EXT) drop perturbations. Ten healthy older ( $71.4 \pm 1.44$  years) and younger adults ( $26.2 \pm 1.63$  years) stood atop a moveable platform and received blocks of twelve consecutive EXT and SLF drop perturbations. Following the last SLF trial, participants received an additional EXT trial spaced 20 min apart to assess retention (EXT RTN) of any modulation effects. Electromyographic (EMG) activity was recorded bilaterally over the sternocleidomastoid (SCM), vastus lateralis (VL), biceps femoris (BF), medial gastrocnemius (MG), and tibialis anterior (TA). Whole-body kinematics and kinetic data were recorded. Stability in the antero-posterior direction was quantified using the margin of stability (MoS). Compared with EXT trials, both groups reduced SCM peak amplitude responses during SLF and EXT RTN trials. VL/BF and TA/MG coactivation were reduced during SLF FTR compared to EXT FTR ( $p < 0.05$ ) with reduced peak vertical ground reaction forces (vGRF) in both younger and older adults ( $p < 0.05$ ). Older adults increased their MoS during SLF FTR compared to EXT FTR ( $p < 0.05$ ). Both groups performed more eccentric work during SLF trials compared to EXT ( $p < 0.05$ ). These findings indicate that abnormal startle effects with aging may interfere with balance recovery and increase risk of injury with external balance perturbations. Motor prediction may be used to acutely mitigate abnormal startle/postural responses with aging.

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## 1. Introduction

With advancing age, deficits in the control of balance stability increase risk of falls and related injuries. Studies of human freefalls show rapid and exaggerated whole-body postural responses that reduce in magnitude over repeated trials and are exaggerated in the first trial (termed first trial responses (FTRs)) (Greenwood and Hopkins, 1976; Jones and Watt, 1971). FTRs resemble general-

ized muscle activity evoked by strong sensory stimuli such as a loud sound that triggers a startle reaction (Greenwood and Hopkins, 1976; Sanders et al., 2015) suggesting that a startle-like reflex contributes to the exaggerated postural FTRs.

Startle-like FTRs are normally eliminated or reduced in magnitude using motor prediction through self-delivered stimulus application. For example, during self-activated drop perturbations (SLF) in younger adults, ankle muscle co-activation and landing impact force decreased (Fu and Hui-Chan, 2002, 2007) compared to externally-triggered (EXT) drop perturbations. Differences in postural responses between EXT and SLF drop perturbations suggest that modulation of startle-like responses via motor prediction may reduce the potential startle component superimposed onto the balance stabilizing responses affecting landing responses.

With aging, abnormal spatial and temporal postural response characteristics for stance and gait perturbations have been reported (Allum et al., 2002; Nagai et al., 2011; Tresch et al., 2014). In addition, similarities between altered acoustic startle incidence, timing, and magnitude properties (Kofler et al., 2001;

*Abbreviations:* BF, biceps femoris; Col, co-contraction index; CoM, center of mass; CoM<sub>low</sub>, center of mass at lowest point after ground contact; EMG, electromyography; EXT, externally triggered; EXT RTN, externally triggered retention trial; FTR, first trial response; GC, ground contact; MG, medial gastrocnemius; MoS, margin of stability; SCM, sternocleidomastoid; SLF, self-triggered; TA, tibialis anterior; vGRF, vertical ground reaction force; VL, vastus lateralis; X<sub>CM</sub>, extrapolated center of mass.

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Ludewig et al., 2003) and postural reactions with older age, have been proposed during recumbent freefall perturbations of the head-trunk (Bisdorff et al., 1995). However, while posture/startle responses show abnormalities with aging, their interactive effects on standing balance recovery are unknown (Granacher et al., 2011; Tresch et al., 2014). Determining how age-related changes in FTRs impact postural control could elucidate whether these phenomena serve as protective or disruptive mechanisms in stabilizing balance.

In addition to the age-associated limitations in reactive balance control, studies of anticipatory postural adjustments during planned movements have shown delayed timing and reduced magnitude changes (Kanekar and Aruin, 2014). However, predictive motor capacity remains intact. Thus, modulation of the postulated early startle component in the FTR through motor prediction could be used to alter abnormal startle/postural reactions in older individuals. Alternatively, impaired motor prediction could contribute to abnormal startle modulation and further disrupt effective balance recovery.

During landing responses, the dissipation of kinetic energy is crucial in reducing ground impact forces experienced by supporting tissues and reducing the risk of injury, pain, and instability. Softer landings include greater knee flexion and active eccentric work done by the lower extremity muscles (Butler et al., 2003). Alternatively, stiff landings are characterized by reduced knee and ankle joint flexion, less active eccentric work, and greater peak vertical ground reaction forces (vGRFs) (Devita and Skelly, 1992; Riemann et al., 2002). Differences in energy dissipation performance between younger and older adults involving limited knee flexion with increased muscle co-activation and delayed onset timing of knee muscle contractions during planned voluntary actions such as drop jumps and stair descent have been identified (Hsu et al., 2007; Saywell et al., 2012; Stelmach et al., 1990). Whether these differences occur for unplanned reactive movements such as following drop perturbations of the standing support surface is unknown. Moreover, the role of motor prediction in improving potentially harmful landing strategies has not been established. Modulation of landing control strategies by motor prediction in older adults would suggest that startle-like responses may affect landing control and balance stability through increased joint stiffness and peak impact forces.

Accordingly, the purpose of this pilot study was to characterize the modulatory effects of motor prediction on startle-like landing FTRs during SLF and EXT drops perturbations of the standing support surface in younger and older adults. We hypothesized that compared to EXT FTRs, SLF FTRs would show increased eccentric work, reduced peak vGRF and reduced balance instability that would be retained in a subsequent EXT retention trial (EXT RTN).

## 2. Methods

### 2.1. Participants

Ten healthy older (5 men; age =  $71.4 \pm 1.44$  years) and young adults (6 men; age =  $26.2 \pm 1.63$  years) participated in the study. Participants were without neurologic or musculoskeletal pathology or deficits which could limit functional activities. Each participant provided informed consent in accordance with the Institutional Review Board of the University of Maryland, Baltimore and the Baltimore Veteran's Administration Medical Center.

### 2.2. Experimental setup

Each session consisted of twelve EXT and SLF drop perturbations with EXT trials preceding SLF. To minimize

habituation, participants received no practice trials and twenty minutes were allotted between conditions (Mang et al., 2012). Following the SLF condition, participants received another EXT trial 20 min after to assess retention of modulation effects. To reduce vGRFs and minimize injury risk, a counterbalancing mass system was used (Greenwood and Hopkins, 1976) to control platform acceleration. The mass was attached to the drop platform through a pulley-cable arrangement. Drop platform acceleration was adjusted such that:  $\text{acceleration} = (M_p - M) \cdot g / (M_p + M)$ , where  $M_p$  is the participant's mass (kg),  $M$  is the counter mass, and  $g$  is acceleration due to gravity. A standardized acceleration of  $4.91 \text{ m/s}^2$  was chosen to reduce peak vGRF to  $1.5 \times M_p$  equaling the peak vGRF during stair descent (Stacoff et al., 2005).

### 2.3. Electromyography

Electromyographic (EMG) activity was recorded (Noraxon, Inc., Scottsdale, AZ) bilaterally over the sternocleidomastoid (SCM), vastus lateralis (VL), biceps femoris (BF), medial gastrocnemius (MG), and tibialis anterior (TA) muscles with a sampling frequency of 1500 Hz. Signals were band-pass filtered (16–500 Hz), full-wave rectified, and low pass filtered at 50 Hz using a digital 4th order Butterworth filter. EMG data were analyzed with custom written Matlab programs (The MathWorks, Inc. Natick, MA). Similar to previously described studies, EMG onset was defined relative to perturbation onset as the time when the rectified EMG value exceeded 3 standard deviations (SD) from mean baseline level for 30 ms (MacKinnon et al., 2007; Mille et al., 2014; Rogers et al., 2011; Sanders et al., 2015). Peak EMG amplitude was calculated as the first maximum EMG value within 120 ms of drop perturbation onset (Barker et al., 2014). Knee and ankle co-contraction indices (Col) were calculated over a period of 100 ms preceding ground contact (GC) and defined as the ratio of twice the integrated EMG activity of the less active muscle, divided by the sum of the integrated EMG activity of the two contracting muscles (Falconer, 1985).

### 2.4. Kinematic and kinetic data collection

Kinematic data were collected at 120 Hz using a 10 camera motion capture system (Vicon-USA, Denver, CO) and low-pass filtered offline at 5 Hz with a 4th order Butterworth filter. Reflective markers were placed on the head and bilaterally on the acromion process, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, lateral epicondyle of the femur, lateral malleolus, first metatarsal, heel, and drop platform to determine movement onset. Platform movement onset was defined as the time when the vertical component of the platform marker trajectory reached  $-2\text{SD}$  of baseline. A five-segment two-dimensional kinematic model was developed to calculate body movements. Ground reaction forces were collected at 600 Hz by two force platforms located underneath the drop platform (Advanced Mechanical Technology Inc., Watertown, MA). Kinetic data were time-synchronized to kinematic data and low-pass filtered at 25 Hz with a 4th order Butterworth filter. Force values were normalized by the participant's mass.

### 2.5. Measurement of balance stability

Stability in the antero-posterior direction was quantified using the margin of stability (MoS) (Hof et al., 2005). Balance recovery from vertical drop perturbations primarily consisted of a generalized flexion response of the body with startle-like responses likely contributing to a tendency to fall forward on landing. Therefore, subsequent analysis was restricted to the anterior-posterior direction. MoS and parameters used to compute MoS were assessed at

the point of maximum downward displacement of the CoM after GC ( $CoM_{low}$ ).  $CoM_{low}$  was chosen as a marker for the completion of landing (Bates et al., 2013). MoS was calculated as follows:  $MoS = BoS - X_{CM}$  where BoS is the anterior boundary of the base of support. The heel marker indicated the posterior boundary while the marker at the distal end of the first metatarsal indicated the anterior boundary. Extrapolated CoM ( $X_{CM}$ ) was obtained using the following equation:  $X_{CM} = P_{CM} + V_{CMx} / \sqrt{g/l}$  where  $P_{CM}$  is the anterior-posterior distance between the initial position of the first metatarsal marker and CoM vertical projection,  $V_{CMx}$  is the anterior-posterior velocity of the CoM,  $g$  is the acceleration due to gravity, and  $l$  is the distance between the CoM and the ankle joint center. A positive stability margin indicates that the CoM motion state is within the stability limits.

## 2.6. Measurement of mechanical work

CoM work rate was computed based on the dot product of vGRF and CoM velocity (Cavagna, 1975; Donelan et al., 2002). CoM work was examined from GC to  $CoM_{low}$  by numerically integrating CoM work rate. Negative values for work indicate eccentric work. Work measures were normalized by the participant's mass.

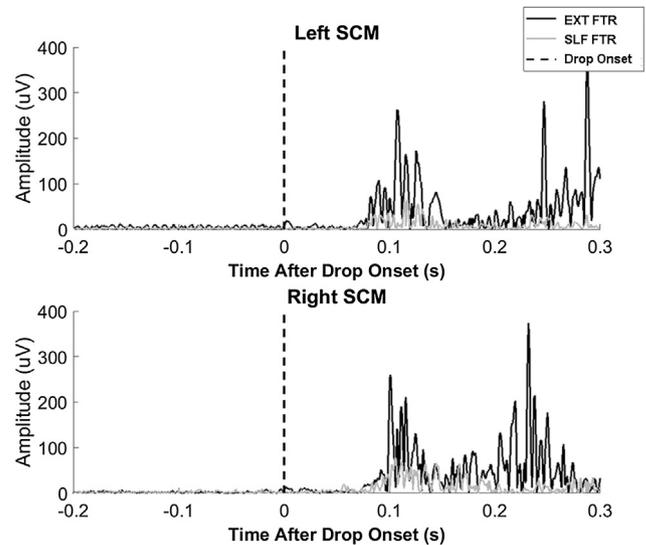
## 2.7. Statistical analyses

All descriptive statistics are reported as mean  $\pm$  standard error (SE). Results were analyzed using SPSS 22 software. Prior to statistical analysis, all data were examined using the Shapiro-Wilk test. Peak EMG activity was not normally distributed and was log-transformed to achieve normality. All remaining datasets were normally distributed (Shapiro-Wilk test,  $p > 0.05$  throughout). T-tests were used to assess differences in peak EMG FTR between participants' EXT FTR, subsequent SLF, and EXT RTN conditions. A two-way repeated measures ANOVA (group: old vs. young, condition: EXT FTR vs SLF FTR vs EXT RTN) was used to analyze the modulatory influences of motor prediction on kinematic, kinetic, and energetic data. Following the omnibus test, group differences were compared using one-way ANOVAs. Multiplicity of testing was addressed by controlling the rate of false discovery (Benjamini and Hochberg, 1995). Results were considered significant at the  $p \leq 0.05$  level with appropriate adjustment for the control of false discovery rate. Pearson correlations were used to determine the association between mechanical work and peak vGRFs.

## 3. Results

Representative FTR bilateral SCM EMG activity during EXT and SLF conditions is shown in Fig. 1. Rapid, phasic, bilateral and synchronous SCM activity within 120 ms after stimulus onset is a hallmark of startle responses (Carlsen et al., 2007) and was present during all FTRs for EXT, SLF, and EXT RTN conditions across both groups. Representative EMG patterns during EXT FTR and SLF FTR for an older adult are shown in Fig. 2. Muscle onset latencies for older adults were delayed across all muscle groups compared to young (Table 1,  $p < 0.05$ ). Both groups showed longer TA onset latencies during SLF FTR compared to EXT FTR ( $p < 0.05$ ). No significant changes in response latencies were present in SCM across both groups between conditions.

Peak EMG response amplitude for each muscle during EXT FTR was compared to SLF FTR and EXT RTN using paired t-tests with an adjusted significance level set at  $p < 0.012$ . SCM responses were significantly reduced during SLF and EXT RTN trials compared to EXT FTR in both groups ( $p < 0.012$ ). No change in lower extremity peak EMG response amplitudes was present between EXT FTR and SLF FTR for either group ( $p > 0.012$ ).



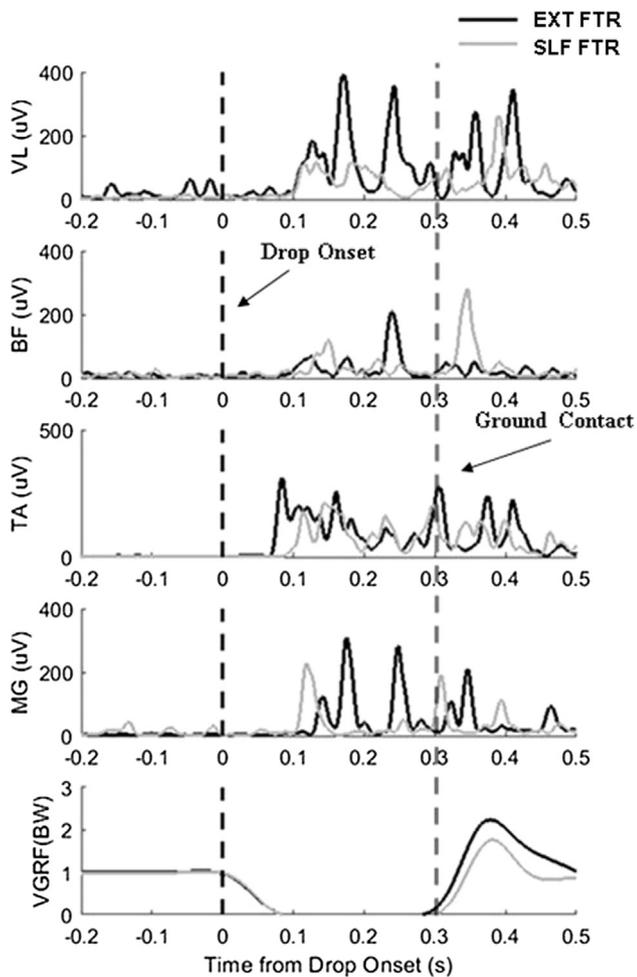
**Fig. 1.** Representative example trial of electromyographic (EMG) responses from bilateral sternocleidomastoid neck muscles following an externally triggered first trial response (EXT FTR) and self-triggered first trial response (SLF FTR) to drop perturbation of the standing support surface in older adult.

There was a significant main effect of age for both VL/BF Col [ $F_{(1,28)} = 22.47$ ,  $P < 0.001$ ] and TA/MG Col [ $F_{(1,28)} = 25.02$ ,  $P < 0.001$ ]. Older adults landed with greater VL/BF Col and TA/MG Col across all conditions compared to young adults (Fig. 3;  $p < 0.05$ ). VL/BF and TA/MG Col were significantly reduced when comparing EXT FTR vs. SLF FTR ( $p < 0.05$ ) among both groups. No significant differences were present between EXT FTR vs. EXT RTN and SLF FTR vs. EXT RTN across groups for VL/BF and TA/MG Col (Fig. 3;  $p > 0.05$ ).

A significant interaction of condition and age was found for hip flexion angle [ $F_{(1,28)} = 25.23$ ,  $P < 0.001$ ] and knee flexion angle [ $F_{(1,28)} = 27.25$ ,  $P < 0.001$ ] at  $CoM_{low}$ . Older adults had greater hip flexion (Fig. 4;  $p < 0.05$ ) and less knee flexion (Fig. 4;  $p < 0.05$ ) during EXT FTRs compared to young adults. No significant differences in all joint flexion angles were found between old and young adults during SLF trials. Among older adults, hip flexion angle at  $CoM_{low}$  during SLF FTR and EXT RTN was significantly less than EXT FTRs (Fig. 4;  $p < 0.05$ ) and knee flexion at  $CoM_{low}$  during SLF FTRs was significantly greater than EXT FTRs (Fig. 4;  $p < 0.05$ ). No significant differences were found between SLF and EXT RTN trials for hip and knee flexion angles for both groups.

A significant main effect of condition on peak vGRF [ $F_{(2,27)} = 12.48$ ,  $p < 0.001$ ] was present. Both groups significantly reduced peak vGRFs during SLF FTR compared to EXT FTR (Fig. 5;  $p < 0.05$ ). No differences were present between EXT FTR vs. EXT RTN trials and SLF FTR vs. EXT RTN trials across both groups. Post-hoc analysis revealed a statistically significant difference between groups as determined by one-way ANOVA for EXT FTR [ $F_{(1,28)} = 93.22$ ,  $p < 0.001$ ], SLF FTR [ $F_{(1,28)} = 90.51$ ,  $p < 0.001$ ], and EXT RTN [ $F_{(1,28)} = 65.86$ ,  $p < 0.001$ ]. Old adults landed with greater impact force compared to younger adults for all conditions ( $p < 0.05$ ).

MoS was smaller among older adults during EXT FTRs compared to younger adults ( $p < 0.05$ ; Fig. 6). No significant differences in MoS during SLF FTR ( $p = 0.86$ ) and EXT RTN ( $p = 0.28$ ) were found between the groups. Older adults showed increased MoS during SLF FTRs compared to EXT FTRs ( $p < 0.05$ ). No significant difference was found when comparing EXT FTR to EXT RTN trials among older adults. Younger adults showed a significant difference in MoS between EXT FTR and EXT RTN conditions ( $p < 0.05$ ).



**Fig. 2.** Representative muscle activation patterns during EXT FTR (Black) and SLF FTR (Grey) for an older adult. Muscles activity was recorded bilaterally for vastus lateralis (VL), biceps femoris (BF), medial gastrocnemius (MG), and tibialis anterior (TA) muscles. Vertical lines indicate the onset of platform release and ground contact.

There was a significant main effect for condition on the eccentric work done [ $F_{(2,27)} = 11.13$ ,  $p = 0.002$ ]. Both groups performed less eccentric work during EXT FTR compared to SLF FTR ( $p < 0.05$ , Fig. 7) but showed no significant differences between SLF FTR and EXT RTN trials. Post-hoc analysis revealed a statistically significant difference between groups as determined by one-way ANOVA for EXT FTR [ $F_{(1, 28)} = 6.07$ ,  $p = 0.02$ ], SLF FTR [ $F_{(1, 28)} = 5.39$ ,  $p = 0.03$ ], and EXT RTN [ $F_{(1, 28)} = 6.38$ ,  $p = 0.02$ ]. Old adults landed with less eccentric work (more negative work done)

**Table 1**

Group mean ( $\pm$  SE) EMG onset latencies (ms) for first trial responses across externally-triggered (EXT), self-triggered (SLF), and retention trials (EXT<sub>RTN</sub>) in healthy young and young adults.

	Old			Young		
	EXT	SLF	EXT <sub>RTN</sub>	EXT	SLF	EXT <sub>RTN</sub>
EMG Response latency (ms)						
SCM	75.42 $\pm$ 5.23 <sup>s</sup>	82.38 $\pm$ 9.20 <sup>†</sup>	78.47 $\pm$ 9.07 <sup>†</sup>	64.26 $\pm$ 6.05	70.16 $\pm$ 6.38	63.81 $\pm$ 8.28
VL	92.44 $\pm$ 5.73 <sup>†</sup>	96.08 $\pm$ 5.71 <sup>†</sup>	91.69 $\pm$ 4.66 <sup>†</sup>	81.97 $\pm$ 3.77	83.96 $\pm$ 4.31	83.57 $\pm$ 4.29
BF	106.78 $\pm$ 6.23 <sup>†</sup>	108.78 $\pm$ 4.00 <sup>†</sup>	108.74 $\pm$ 5.68 <sup>†</sup>	99.61 $\pm$ 4.15	95.59 $\pm$ 4.48	94.36 $\pm$ 5.02
TA	82.68 $\pm$ 4.94 <sup>†</sup>	102.68 $\pm$ 2.86 <sup>††</sup>	79.54 $\pm$ 4.41 <sup>†</sup>	70.52 $\pm$ 4.81	90.53 $\pm$ 3.01 <sup>†</sup>	72.07 $\pm$ 4.71
MG	88.10 $\pm$ 4.92 <sup>†</sup>	80.56 $\pm$ 5.48 <sup>†</sup>	87.01 $\pm$ 7.55 <sup>†</sup>	76.42 $\pm$ 4.41	65.08 $\pm$ 3.97	75.55 $\pm$ 5.82

<sup>s</sup> Denotes significance for corresponding measure between groups,  $p < 0.05$ .

<sup>†</sup> Denotes significance from (EXT) trials within-group,  $p < 0.05$ .

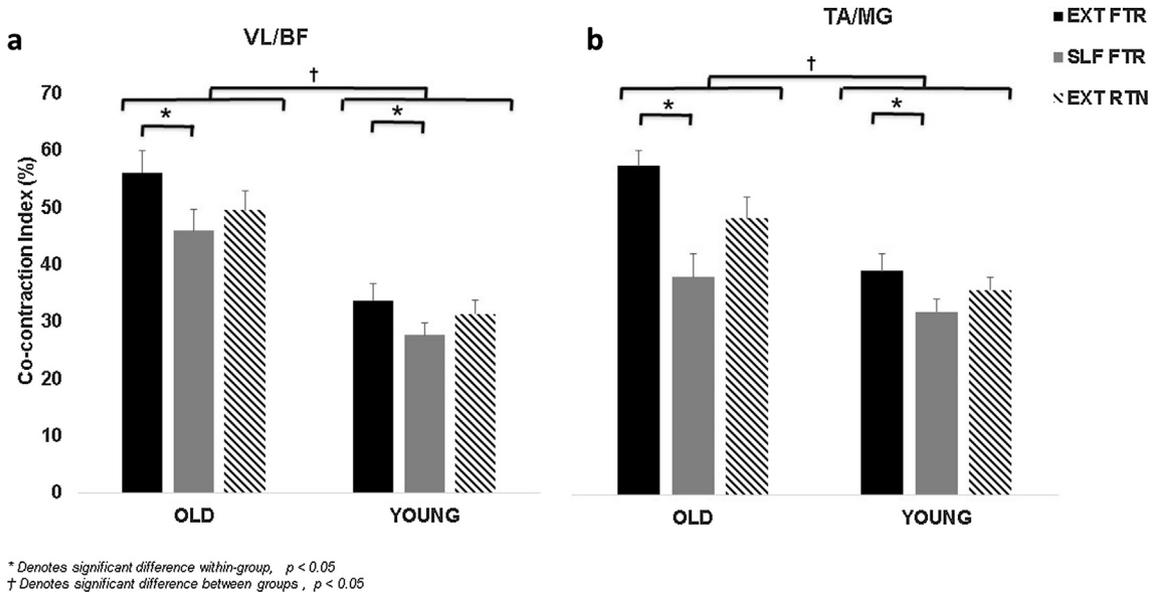
compared to younger adults for all conditions ( $p < 0.05$ ). There was a significantly positive moderate correlation between eccentric work and peak vGRF ( $r = 0.495$ ,  $p < 0.05$ , Fig. 8).

#### 4. Discussion

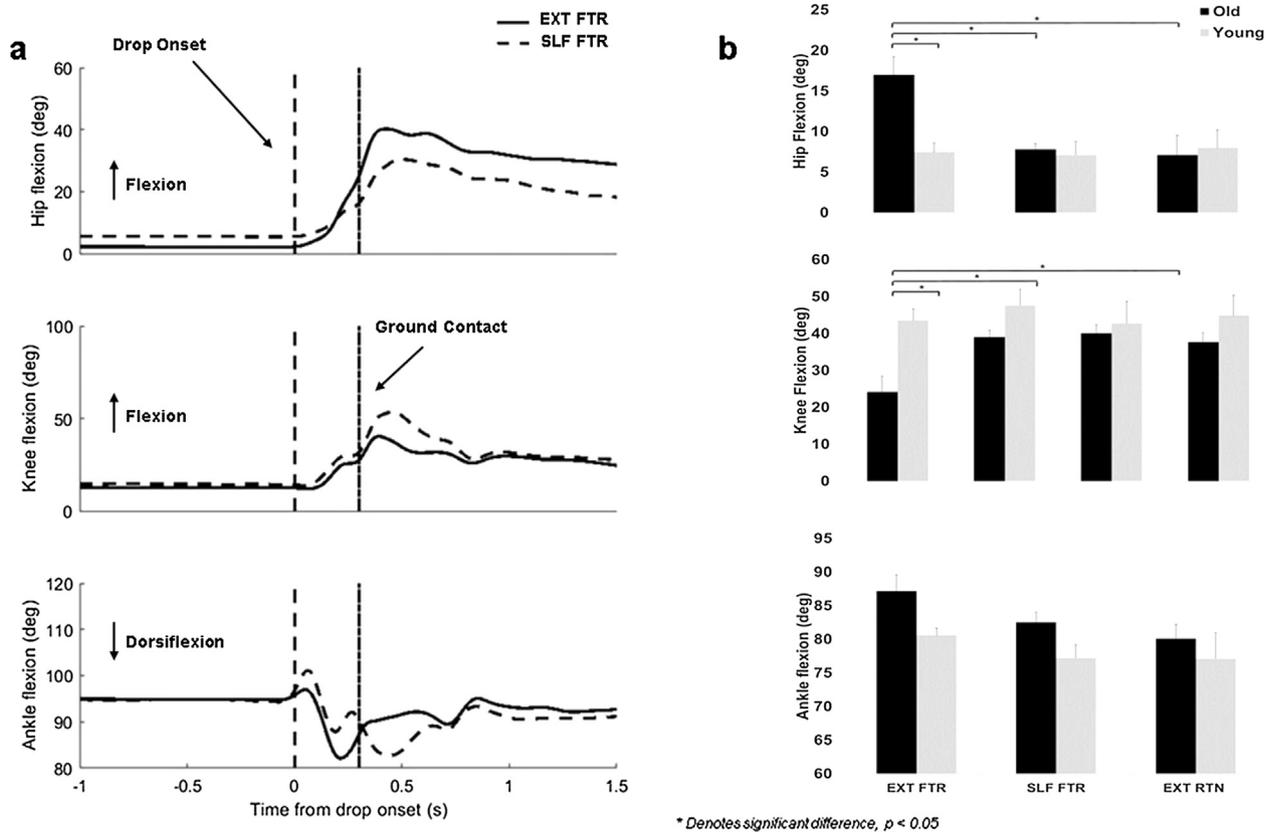
In support of our hypothesis, landing responses were modulated across both groups through motor prediction resulting in reduced knee and ankle co-contraction, and decreased peak vGRFs compared to EXT FTR. Older adults, through motor prediction, reduced balance instability compared to EXT FTRs. Rapid, bilateral and synchronous SCM activation was present in all trials but peak response amplitude was less during SLF FTRs compared to EXT FTRs. The findings are consistent with a previous study which observed modulation of startle-like responses in the SCM characterized by reduced magnitude (Valls-Sole et al., 1997). Our findings suggest that the differences observed were, at least in part, attributable to a prominent startle component in the EXT FTRs as shown previously (Sanders et al., 2015), and that older adults can modulate startle-like responses through motor prediction. This may help guide training interventions aimed at altering central nervous system response to unexpected perturbations, resulting in improved balance stability and attenuated impact force from falls.

A previous study showed TA/MG co-contraction decreased in younger adults during self-initiated above-ground drops compared to externally triggered, and was associated with reduced peak vGRFs (Fu and Hui-Chan, 2002). In our study, onset of TA EMG response following platform release was significantly delayed by  $\sim 20$  ms ( $p < 0.05$ ) for both groups during SLF FTRs compared to EXT FTR, resulting in decreased TA/MG co-contraction and peak vGRFs. The difference in modulation patterns between EXT FTR and SLF FTR TA onset latency suggests that reducing ankle muscle co-activation may minimize the severity of landing impact forces under the influence of supraspinal control.

In the present study, older adults had increased knee and ankle co-contraction at GC compared to younger adults, suggesting increased joint stiffness in the lower extremities with greater limb rigidity. Given the large external loads applied to the lower limbs at landing over a short period of time, older adults may have been unable to reactively respond quickly to counter these potentially damaging forces. Thus, older adults increased their lower limb stiffness before landing as a way to stabilize the lower extremities while minimizing sagittal and downward body motion to guard against collapse. However, in doing so, older adults increased the risk of injury during landing due to greater vGRF compared to younger adults, as well as increased the risk of instability due to decreased MoS. This finding is in agreement with a previous study which linked elevated TA/MG co-contraction levels with increased risk of falls assessed during a dynamic balance assessment task (Nelson-Wong et al., 2012).



**Fig. 3.** Group mean  $\pm$  1 standard error (SE) VL/BF co-contraction index (Col) (left), and TA/MG co-contraction index (Right) during externally triggered (EXT FTR) and self-triggered (SLF FTR) conditions as well as the subsequent retention trial (EXT RTN).



**Fig. 4.** Representative older adult (LEFT) kinematic time series profiles in order from the top: hip, knee, and ankle joint angles, and group means  $\pm$  1 SE (RIGHT) of mean joint angles at COM<sub>low</sub> for young and older adults.

Knee flexion during SLF FTRs was greater than EXT FTRs among both groups, allowing greater attenuation of peak vGRFs during landing. Reduced knee flexion among older adults during EXT FTRs may result in the knee receiving larger compressive impact forces which can damage knee ligaments and joints, placing older

individuals at higher risk for injury (Coventry et al., 2006; Lephart et al., 2002; Yeow et al., 2011). Increased knee flexion during SLF FTRs coincided with greater eccentric work compared to EXT FTRs. Lower extremity muscles generate eccentric work, facilitating absorption of kinetic energy from other tissue structures

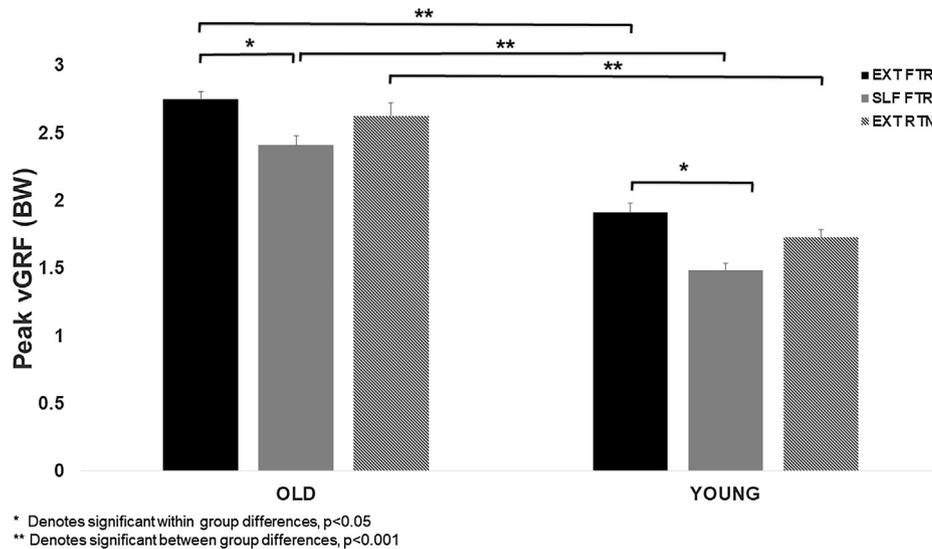


Fig. 5. Group means  $\pm$  1 SE peak vertical ground reaction forces (vGRF) normalized by body weight.

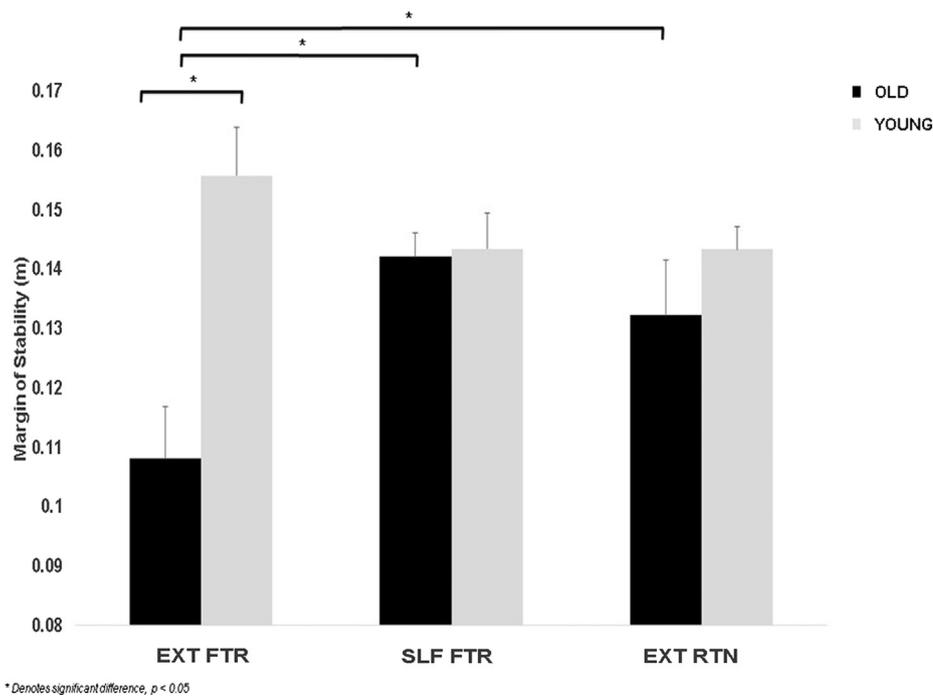
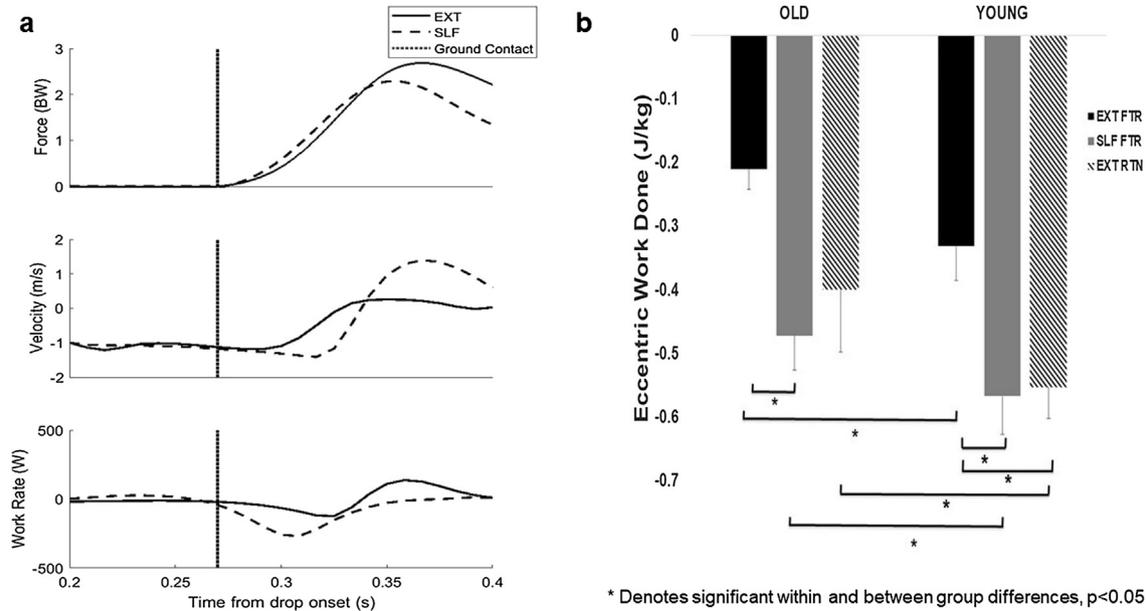


Fig. 6. Group means  $\pm$  1 SE of margin of stability (MoS) for EXT FTR, SLF FTR, and EXT RTN FTRs.

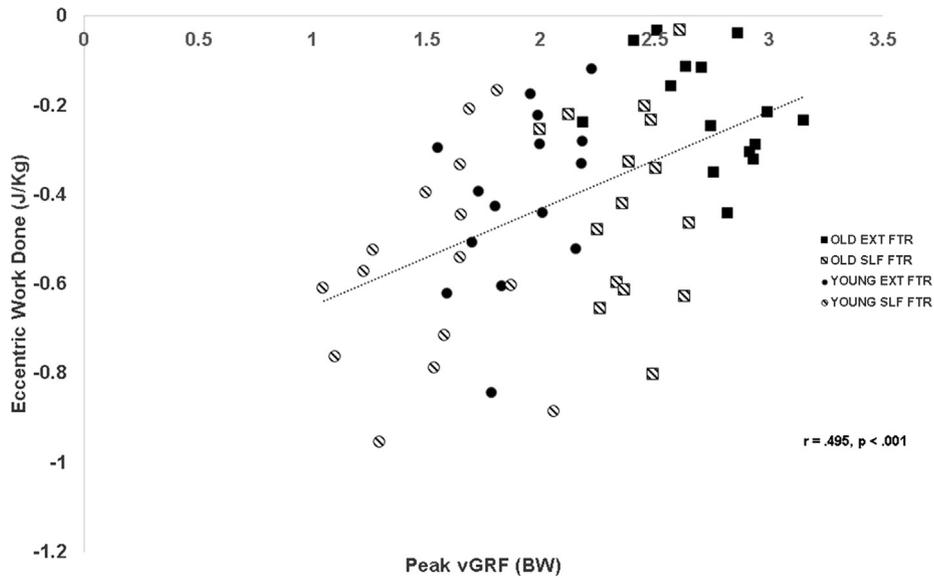
such as cartilage, ligaments and bones. This helps to decelerate the downward motion of the CoM and likely reduces the risk of injury (Lafortune et al., 1996; Mizrahi and Susak, 1982). Moreover, increased eccentric work significantly correlated with reduced peak vGRF. Therefore, interventions aimed at increasing knee flexion through eccentric thigh extensor muscle control affecting shock absorption during landing should be considered as a potential means of decreasing the risk of injury from excessive vGRFs.

Similar to other balance perturbations studies, older adults showed deficits in the control of balance stability (Carty et al., 2011; Karamanidis et al., 2008; Mille et al., 2013). Older adults demonstrated increased hip flexion and less knee flexion during the landing phase of EXT FTRs compared to younger adults. Age-

related increases in hip/trunk flexion may reflect decreased control of trunk musculature (Hwang et al., 2008), decreased muscle strength, or an attempt to reduce the internal knee extensor moment during landing (Torry et al., 2004). Reduced knee flexion at landing could indicate an age-related reduction in knee extensor control or eccentric contractile force. Alternatively, older adults may be more susceptible to the effects of abnormal startle responses. When participants had temporal certainty of the drop perturbation onset during SLF trials, they likely suppressed startling themselves through feedforward mechanisms (Sanders et al., 2015). Improved balance stability in older adults during SLF FTRs coincided with reduced peak SCM amplitude, and reduced hip flexion, both classical markers of startle reactions (Yeomans



**Fig. 7.** (A) Representative time series of vertical ground reaction force (vGRF) (TOP), center of mass velocity (MIDDLE), and work rate (BOTTOM) for EXT (solid line) and SLF (dashed line) condition for an older adult. (B) Mean  $\pm$  1 SD eccentric work normalized by participant mass for each condition.



**Fig. 8.** Scatterplot showing association between eccentric work and peak vGRFs.

et al., 2002). In this regard, a previous study showed an unexpected, startling auditory stimulus triggers several neuromuscular events including increased hip flexion (Brown et al., 1991). Altogether, these findings support the possibility of startle-like reactions superimposed onto balance recovery responses which interfere with recovering balance stability (Nonnekes et al., 2015).

Neither group retained landing control strategies developed during SLF FTRs in subsequent EXT RTN trials. One potential factor which may have limited the retention of SLF landing control strategies is the lack of variability. Introducing variability in the sequence of the drop perturbation type may have facilitated longer retention. Additionally, participants received no feedback on how their strategies influenced vGRFs. Individualizing the training program and allowing feedback may be beneficial in facilitating the

retention of landing strategies to better promote attenuation of large vGRFs (Mansfield et al., 2007).

Differences between EXT FTRs and SLF FTRs in both groups likely occurred for two reasons. First, feedforward modulation of brainstem and spinal circuits over corticofugal and corticospinal pathways during SLF drops may have accounted for the differences. Physiological studies have linked the contribution of brainstem structures to postural control during both reactive and proactive postural control (Nonnekes et al., 2015; Tresch et al., 2014). Second, modulated muscle onset latencies and CoI were likely due to changes in predictive control. Predictive control is associated with the concept of an internal model and may allow the central nervous system to estimate the consequences of motor commands by incorporating a representation of the body and external envi-

**Table 2**  
Measures of trial order effect.

	Group 1		Group 2		Interaction	
	EXT (n = 10)	SLF (n = 10)	SLF (n = 5)	EXT (n = 5)	F (1,13)	p
Old						
Peak VGRF (BW)	2.68 ± 0.77	2.35 ± 0.56	2.49 ± 0.08	2.86 ± 0.11	0.16	0.90
Eccentric Work (J/kg)	−0.21 ± 0.04	−0.48 ± 0.69	−0.45 ± 0.10	−0.21 ± 0.06	0.04	0.85
Young						
Peak VGRF (BW)	1.93 ± 0.72	1.53 ± 0.10	1.51 ± 0.14	1.88 ± 0.10	0.02	0.88
Eccentric Work (J/kg)	−0.34 ± 0.07	−0.54 ± 0.08	−0.62 ± 0.11	−0.31 ± 0.10	0.50	0.49

ronment to determine the motor commands required to perform specific tasks (Wolpert and Miall, 1996). In the present study, muscular activity was centrally modulated which may have adjusted joint stiffness when temporal certainty of the drop perturbation was provided. Alternatively, knowledge of the forthcoming drop perturbation may have altered the participants' behavioral state by decreasing their level of arousal. An essential component of fear of falling is the perceived risk of injury as a result of instability. Increased ankle joint stiffness is an anxiety-mediated response in order to limit CoM movement by achieving a stiffer mechanical system (Brown et al., 2006; Carpenter et al., 1999; Carpenter et al., 2001). Therefore, decreased arousal during SLF FTRs may have contributed to the observed differences.

There were several limitations associated with this study. First, this study involved a small sample of older participants who were healthy and moderately active. Therefore, the results may not generalize to older adults with mobility or balance limitations. Secondly, the presentation order of the drop perturbation stimuli was non-randomized. Therefore habituation effects obtained during EXT trials may have carried over to SLF FTRs. However, a different cohort of five healthy previously untested older (2 men; age = 75.6 ± 1.14 years) and younger adults (3 men; age = 24.7 ± 1.23 years) received 12 sequential SLF trials followed by 12 EXT trials spaced 20 min apart, and no interaction effect for order on primary response variables (vGRF and eccentric work) was found, indicating that habituation carryover effects between conditions were likely minimized (Table 2). The onset of the initial automatic postural response typically occurs 70–120 ms after external perturbations (Horak, 2006). Therefore it is plausible that the observed responses involve an overlap of startle and postural responses. Lastly, while our study objective was to understand the influence of age and motor prediction on neuromuscular control of landing while standing, future studies should introduce dynamic task conditions such as perturbed drops while walking which may more fully characterize the responses observed during daily functional activities (Nieuwenhuijzen and Duysens, 2007).

In conclusion, older adults can modulate startle/postural neuromuscular responses via motor prediction in order to reduce landing impact forces and enhance balance stability. The data may be beneficial in the development of scientifically grounded therapeutic interventions aimed at enhancing balance recovery by utilizing the central neural modulatory capacity in older adults through motor prediction to improve balance stability and reduce impact forces during falls. Furthermore, eccentric muscular control should be targeted in rehabilitation approaches along with training to enhance lower extremity eccentric strength among older adults.

#### Declaration of Competing Interest

The authors of this paper have no financial or personal relationships with other people or organizations that could inappropriately influence our work.

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