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Older adults exhibit variable responses in stepping behaviour following unexpected forward perturbations during gait initiation

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ABSTRACT

With the socioeconomic burden associated with falls expected to rise as the average age of the Canadian population increases, research is needed to elucidate the nature of postural responses generated by older adults (OA) following a posture-destabilizing event. This knowledge is even more imperative for novel and difficult tasks, such as gait initiation (GI), a task known to pose a postural threat to stability for OA. A common technique to regain stability following an unexpected perturbation is reactive stepping. A deficiency in the execution of a reactive control strategy following a destabilizing event may be the cause of many unexpected falls in OA. The **purpose** of this study is to explore age related changes in the nature of these responses during a challenging GI task combined with an unexpected forward perturbation of the support surface. A total of 18 young adults (YA) and 16 OA performed 36 trials containing 20 unexpected perturbations. We calculated step width, length, time and COM velocity in the first unperturbed step and the second perturbed step. Results revealed that, during unperturbed GI, OA had a reduced forward velocity and took shorter, faster steps. Following forward perturbations, OA altered stepping patterns, perhaps to reduce single support duration, via reduced base of support and shorter step length compared to YA. Additionally, OA executed both forward and backwards directed steps however YA only generated forward steps. Regression analyses revealed that reduced forward velocity was predictive of step direction; which is possibly an unfavorable motor control strategy as OA who walk slower generated a posterior directed step immediately following the perturbation. This strategy is of concern as rapid responses by the trail limb are required to recover successfully, and these alterations may be associated with an elevated risk of falls.

1. Introduction

Recent epidemiological data suggest that in Canada alone, > 250,000 injurious falls occur every year amongst the senior population (Public Health Agency of Canada, 2005). Observational data suggests that an incorrect shift of body weight is one of the riskiest movements for older adults (OA), with 41% of observed falls occurring due to this mechanism (Robinovitch et al., 2013). Gait initiation (GI) includes a period of both quiet stance and dynamic locomotion, representing one of many transient volitional tasks requiring a transfer of body weight. During GI, the central nervous system (CNS) must accelerate the center of mass (COM) forward and laterally, while simultaneously reducing the base of support (BOS); essentially creating an internal perturbation (Elble, Moody,

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Leffler, & Sinha, 1994) which must be carefully controlled to ensure stability is maintained throughout this dynamic task (Mickelborough, van der Linden, Tallis, & Ennos, 2004). Previous studies have observed that OA exhibit altered mechanics during GI, for example Mbourou, Lajoie, and Teasdale (2003) reported that OA tend to take shorter steps and have more variability in the first step length; this result became more apparent with increasing age and number of reported falls. A study by Caderby, Yiou, Peyrot, Begon, and Dalleau (2014) revealed that gait velocity in the anterioposterior (AP) direction was related to mediolateral (ML) instability during GI (Caderby et al., 2014). This reduced stability was attributed to insufficient control; at reduced speed, lateral COM movement was less attenuated.

It is imperative to understand alterations in spatial-temporal parameters of gait to indirectly evaluate both stability and future falls risk, especially during challenging locomotor tasks. Many daily activities require the CNS to keep the COM within the confines of the BOS (Maki & McIlroy, 2006); commonly defined as 'stability'. Many volitional activities challenge our ability to maintain stability due to the dynamic nature of surrounding environs. For example, in the course of a given day, our stability is challenged when encountering external objects that require accommodation strategies e.g. stepping over an object. In a similar manner, to initiate gait from quiet stance we must produce a controlled, destabilizing force to move the COM outside of the BOS (Maki & McIlroy, 2006).

In contrast to these volitional tasks, our tasks of daily living also require stabilizing responses to be generated following an unexpected perturbation. In these situations, the CNS is tasked with quickly coordinating a reactive strategy to avoid falling (Lockhart, Smith, & Woldstad, 2005). Reactive stepping is a primary strategy utilized to attenuate the destabilizing effects of an unexpected perturbation (Maki & McIlroy, 2006). Previous research has noted, perhaps in an effort to reduce the likelihood of a forward slip inducing a fall, that both forward and backward directed steps can be generated (Moyer, Redfern, & Cham, 2009). Recovery steps directed posteriorly, termed a trail limb response, are used following the most destabilizing perturbations (Moyer et al., 2009). This trail limb response has been shown to occur in near equal proportion for both younger and OA following a slip on a contaminated vinyl flooring surface (Moyer et al., 2009).

To our knowledge, a limited number of studies have quantified age related differences to AP directed perturbations. Two prior studies (Maki & McIlroy, 2006; McIntosh, Zettel, & Vallis, 2017) have used a robotic platform to elicit an external perturbation; this experimental methodology is unique as perturbations are consistent (e.g. direction, velocity, acceleration, duration, onset) and can be easily controlled in a manner that reduces the likelihood of participants anticipating the exact nature of the perturbation. To date, the majority of robotic platform studies have focused on testing responses to ML directed perturbations, perhaps due to reports of increased ML instability in OA (Hilliard et al., 2008; Maki & McIlroy, 2006; Maki et al., 2000; McIntosh et al., 2017). Recent research from our lab (McIntosh et al., 2017) during a dynamic gait task revealed that recovery steps generated by OA following an unexpected perturbation applied during over ground gait were significantly smaller than their pre-perturbation step, and smaller than all young adult (YA) steps. Interestingly, no changes in step width following AP perturbations applied during over ground gait were observed in either young or OA (McIntosh et al., 2017). A study conducted by Maki and McIlroy (2006) required subjects to step in place following an unpredictable perturbation. Not surprisingly, major differences were observed in the series of steps following perturbation; OA required more steps, perhaps due to their inability to modulate the size of their BOS in the first step following a perturbation (Maki & McIlroy, 2006).

Additional studies have demonstrated significant differences between stepping strategies of older and YA for a variety of postural tasks, including over ground walking in a research laboratory (Tang & Woollacott, 1998) and on a running track (Lockhart et al., 2005) using a slippery surface. In general, these experimental paradigms result in OA generating shorter step lengths (Tang & Woollacott, 1998), reducing time spent in single-support, widening their BOS and adopting a slower gait velocity (Lockhart et al., 2005; Maki & McIlroy, 2006). Slipping is recognized as one of the leading causes of falls, and the proportion of falls caused by slipping is at least 25% (Nagano, Sparrow, & Begg, 2013). Given this startling statistic, it is imperative that age related changes in reactive control strategies following a forward slip are studied, and that mechanical alterations are better understood. During ongoing locomotor tasks (e.g. walking), posterior slips of the support surface have minimal real world relevance; as such, many research studies consider these trials as 'catch' trials (*similar to* McIntosh et al., 2017). Recovering from a forward slip on heel contact (HC) is, arguably a more ecologically valid scenario (e.g. slipping on ice). To our knowledge, only one study has analyzed perturbations delivered during GI (Nagano et al., 2013). In this study, participants initiated walking from a contaminated surface (treated with oil), thereby causing a backward slip of the swing limb during the propulsive phase of GI. Results from this study focused on a kinetic analysis of the foot-ground interaction to ascertain if this could predict likelihood of a slip. Unfortunately, this study did not explore any age related differences in postural responses during this task.

The primary **purpose** of the current study is to discern age related alterations in proactive and reactive dynamic postural control of GI, and to ascertain how these strategies change following a forward perturbation issued during GI that evokes a reactive step. For previously stated reasons, we have elected to issue these perturbations using a robotic platform. It is hypothesized that OA will initiate gait with a reduced forward COM velocity and shorted step length compared to YA. Additionally, we expect that if a forward support surface perturbation is issued during a GI task, OA will have increased difficulty in attenuating and recovering their balance, demonstrated through reduced forward velocity, and a shorter step length immediately following the perturbation as compared to YA. Increased understanding of the mechanisms of these balance recovery strategies is critical since alterations in strategies following slip-like events could be used to better inform fall prevention programs and improve reactive balance.

2. Methods

2.1. Participants and inclusion criteria

Sixteen community dwelling OA (9 males; age: 75.6 ± 5.3 years, height: 1.7 ± 0.1 m, weight: 72.7 ± 13.4 kg) and eighteen healthy university aged YA (10 males; age: 21.7 ± 2.6 years, height: 1.8 ± 0.1 m, weight: 72.8 ± 11.0 kg) volunteered for this study. All subjects had no prior experience with platform perturbation studies, were right foot dominant (Waterloo footedness questionnaire; Elias, Bryden, & Bulman-Fleming, 1998) and had no preexisting, self-reported musculoskeletal, neurological or cardiovascular conditions. All subjects gave written consent to participate; the study was approved by the institutional research ethics board (REB#16OC003).

2.2. Protocol

This study is part of a larger experimental paradigm that was split into two different manuscripts due to fundamental differences in age related responses generated following anterior-posterior (AP) and medial–lateral (ML) perturbations of the support surface (Shulman, Spencer, & Vallis, 2018). Briefly, a total of 27 reflective markers and 5 rigidly mounted triad markers were placed to facilitate estimation of a 13-segment COM model (*adapted from* Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998, through exclusion of rib markers as the harness would occlude markers from cameras). Kinematic markers were sampled at 100 Hz using a 12 camera passive Optitrack system (Natural Point Inc., OR, USA) and data was recorded using Motive software (Natural Point Inc., OR, USA). Gait was initiated from quiet stance on the first of two large force plates, arranged one in front of the other (0.60 × 0.90 m; Advanced Mechanical Technology Inc., MA, USA) sampled at 1000 Hz. Force plates were mounted on top of a custom robotic platform (3 × 5 m) and arranged so that subjects began with both feet in quiet stance on force plate 'one'. Researchers gave a verbal cue to start walking and, in the appropriate trials, AP perturbations were triggered at Step1 HC with force plate 'two' (trigger threshold was set to be ~15% body weight for each participant). Accordingly, the first step was unperturbed and postural responses to the platform motion were apparent starting in Step2. All participants were asked to complete the goal-oriented task ("*Please walk to the end of the platform at a comfortable walking pace"*) and to initiate gait with the right foot. Two, unperturbed practice trials were performed to ensure all participants were familiar with the platform and understood the nature of the goal-directed task; data from these trials was not analyzed. Following a single quiet stance trial, a total of 35 GI trials were collected: 4 forward, 6 backward, 6 left, 4 right and 15 no perturbation (NP). A pseudo-randomized experimental design was utilized to reduce the possibility that participants were anticipating different conditions; within each of the three blocks the number of perturbations in each direction was pre-specified and near equal. Trials were excluded if participants stepped first with their left (non-dominant foot; n = 19; 14 trials for OA, 5 trials for YA). Independent of direction, the perturbation magnitude was a total displacement of 18 cm, and peak velocity and acceleration of 60 cm/s, 2 m/s^2, respectively. A previous study within the lab (McIntosh et al., 2017) indicated that perturbations of this magnitude were destabilizing yet safe for an OA population. Our original perturbation magnitude was based on previously published research from Maki and McIlroy (2006).

As reported previously, this study was part of a larger experimental paradigm that also examined postural responses following ML perturbations. Our experimental design allowed us to trigger AP and ML perturbations (with different thresholds) within one experimental session in a random fashion. This reduced the ability of our participants to anticipate the direction of the platform movement and additionally meant that just one laboratory visit for our participants was required, an important consideration for our OA participants. Given the nature of the responses observed, the present study will only report findings related to stepping responses to NP and AP perturbations; ML perturbation responses were highlighted in a companion paper (Shulman et al., 2018).

2.3. Data processing

All kinematic data was processed using Visual 3D software (Version 6, C-Motion Inc., MD, USA). Data was interpolated to account for marker occlusion (≤10 frames) and then filtered (dual pass 6 Hz Butterworth filter). Gait cycle events that were defined in the steps following GI included; toe-off (TO) and HC. HC was defined using the vertical velocity of the heel marker. On the descent of this sinusoidal signal, the instant in time when the velocity returned to a value of 0.04 m/s (≥10 frames) was denoted HC. This near-zero threshold velocity has been previously identified by our lab group as an accurate and specific method for identifying temporal events (Huntley, Zettel, & Vallis, 2016). GI onset was defined as the instant in time when the heel marker vector first went above this threshold (≥10 frames) and each subsequent HC was defined as the instant when velocity of this marker returned to 0.04 m/s for at least 10 frames. Heel marker position was subtracted from the iliac marker to identify toe-off events (*adapted from* Zeni, Richards, & Higginson, 2008).

Step length and width were defined as the anterior and lateral distances between the heel markers at HC in the sagittal and frontal plane, respectively. Step-time was the duration of the swing-phase, from the instant of TO to HC. Whole-body COM velocity was taken at the instant of each HC for Step1 and Step2 as a measure of spatial temporal control in both the anterior-posterior and medio-lateral directions (HC Velocity$_{AP}$ and HC Velocity$_{ML}$, respectively).

As we were interested in stepping strategies used to prevent a fall following the externally issued perturbation, our analyses focused on Step2, e.g. the step immediately following perturbation onset. While YA always executed a forward step following perturbation onset, we noted during data collection sessions that in some trials, OA generated both forward and backward step responses to the forward support surface translations.

Table 1

Summary of spatial and temporal variables calculated in the first two steps following GI. All dependent variables are displayed as a mean ± standard error. In the event of a statistically significant Age*Direction interaction effect, only the interaction effect is displayed along with the associated F-statistic, effect size ($\eta^2_{partial}$) and power (β); interaction effects are explained, in detail, within the results. All non-significant interaction and main effects have been redacted. NP = no perturbations of the support surface. Note that a negative HC velocity $_{ML}$ represents rightward directed steps.

		Forwards	NP	Backwards	Statistics
Step1 Swing Time (seconds)	OA	0.35 ± 0.01	0.35 ± 0.01	0.35 ± 0.01	**Age ($p < 0.01$)**; $F_{(1, 33)} = 65.11$, $\eta^2_{partial} = 0.43$, $\beta = 1.00$)
	YA	0.41 ± 0.01	0.41 ± 0.01	0.41 ± 0.01	
Step1 HC Velocity$_{ML}$ (m/s)	OA	−0.11 ± 0.01	−0.11 ± 0.01	−0.11 ± 0.01	*No significant Main or Interaction effects*
	YA	−0.10 ± 0.01	−0.11 ± 0.01	−0.11 ± 0.01	
Step1 HC Velocity$_{AP}$ (m/s)	OA	0.61 ± 0.03	0.60 ± 0.03	0.60 ± 0.03	**Age ($p < 0.01$);** $F_{(1, 33)} = 39.83$, $\eta^2_{partial} = 0.31$, $\beta = 1.00$
	YA	0.75 ± 0.04	0.80 ± 0.03	0.80 ± 0.03	
Step1 Step Width (m)	OA	0.12 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	*No significant Main or Interaction effects*
	YA	0.12 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	
Step1 Length (m)	OA	0.42 ± 0.02	0.42 ± 0.02	0.42 ± 0.02	**Age ($p < 0.01$)**; $F_{(1, 33)} = 146.19$, $\eta^2_{partial} = 0.62$ $\beta = 1.00$)
	YA	0.56 ± 0.02	0.57 ± 0.01	0.57 ± 0.01	
Step2 Swing Time (seconds)	OA	0.37 ± 0.02	0.43 ± 0.02	0.36 ± 0.02	**Interaction ($p < 0.01$);** $F_{(1, 33)} = 11.97$, $\eta^2_{partial} = 0.214$, $\beta = 0.99$)
	YA	0.64 ± 0.02	0.48 ± 0.02	0.42 ± 0.03	
Step2 Velocity$_{ML}$ (m/s)	OA	0.01 ± 0.02	0.12 ± 0.02	0.06 ± 0.02	**Interaction ($p < 0.01$)**; $F_{(1, 33)} = 7.42$, $\eta^2_{partial} = 0.14$, $\beta = 0.93$)
	YA	0.18 ± 0.02	0.15 ± 0.02	0.08 ± 0.02	
Step2 Velocity$_{AP}$ (m/s)	OA	0.53 ± 0.05	0.91 ± 0.05	1.08 ± 0.06	**Interaction ($p < 0.01$)**; $F_{(1, 33)} = 6.76$, $\eta^2_{partial} = 0.13$, $\beta = 0.91$)
	YA	1.02 ± 0.07	1.05 ± 0.05	1.18 ± 0.05	
Step2 Step Width (m)	OA	0.09 ± 0.01	0.11 ± 0.01	0.09 ± 0.01	**Interaction ($p < 0.01$)**; $F_{(1, 33)} = 3.85$, $\eta^2_{partial} = 0.08$, $\beta = 0.68$)
	YA	0.16 ± 0.01	0.13 ± 0.01	0.09 ± 0.01	
Step2 Length (m)	OA	0.08 ± 0.04	0.52 ± 0.04	0.60 ± 0.04	**Interaction ($p < 0.01$)**; $F_{(1, 33)} = 20.56$, $\eta^2_{partial} = 0.32$, $\beta = 1.00$)
	YA	0.58 ± 0.03	0.61 ± 0.03	0.71 ± 0.03	

2.4. Statistical analyses

Statistical analyses were performed using SPSS software (Version 24, IBM Corp., New York, USA). A two-way ANOVA was conducted on all dependent measures (gait time, velocity and step width/length), with Perturbation Direction (forward, NP and backward) and Age Group (OA and YA) as independent factors. Post hoc Bonferonni analyses were conducted and corrections were applied, where appropriate. Statistical significance was set to $p = 0.05$. Due to the nature of the experimental design, we performed statistical analyses (ANOVA) to examine if learning occurred in our trial blocks; this analyses revealed no learning or block effect ($p > 0.05$; results not included in the current paper).

Two Pearson correlation analyses were performed (one for each age group due to the nature of the step responses observed) to determine if COM velocity$_{AP}$ at Step2 heel contact was related to the stepping strategy used in the step immediately following perturbation (Step2 length). This analysis permitted us to examine possible mechanisms for the variability observed within our participant groups. We were curious to determine if the magnitude and direction (forward or backward) or the step immediately following the perturbation was related to COM velocity$_{AP}$. Note that trials when participants contacted the floor with the forefoot prior to heel contact ("stutter step") were excluded for this analysis (n = 4 trials total, all OA).

3. Results

For the purpose of clarity Table 1 displays the means ± standard error and summary statistics respectively for standard gait parameter outcomes (e.g. swing time, velocity, step length and width).

3.1. Age related alterations in unperturbed GI

No interaction or main effects of Direction were observed for the first, unperturbed step. A significant Age main effect was however observed for the first unperturbed step (Step1) for swing time, HC velocity$_{AP}$ and length (see Table 1). In general, OA walked with a significantly reduced ($p < 0.05$) velocity$_{AP}$, reduced length and spent less time in single support during this initial step. No main effects were observed for Age in either Step1 velocity$_{ML}$ or Step1 step width.

3.2. Differences in reactive stepping following onset of AP perturbations

A significant Age Group × Direction interaction effect ($p < 0.05$) was observed for Step2 swing time. Post hoc analyses revealed that in comparison to NP, the YA significantly ($p < 0.05$) increased the duration of the swing phase for this step. In contrast, OA did

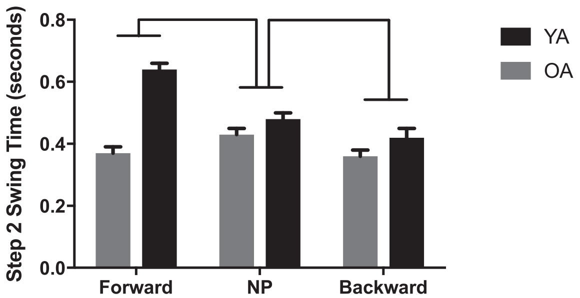

Fig. 1. Duration of the left swing phase (seconds ± standard error) in the second step (Step2) following forward and backward perturbations and in the unperturbed condition (NP). Black bars indicate statistically significant interaction effects; Age*Perturbation direction ($p < 0.05$). Post Hoc analyses revealed that older adults did not alter the time spent in single support following a forward perturbation compared to the no perturbation trials (Ant < NP; $p = 0.31$). In contrast, young adults significantly increased left swing phase following a forward perturbation compared to the NP trials.

not make significant modifications to this step; they spent a similar amount of time in single support as during NP trials (swing time; Fig. 1). A significant Age × Direction interaction effect was observed for Step2 $Velocity_{AP}$ and $Velocity_{ML}$. To place this finding in context, OA Step2 $Velocity_{AP}$ was 50% of that produced by the YA at this phase of balance recovery (see Table 1). Interestingly, it appears that YA increased velocity between Step1 to Step2 as they progressed and accelerated to the end of the platform, however OA decreased velocity over this same time period during the forward perturbation trials (see Table 1). Post hoc analyses revealed a significant effect of Direction (between NP and forward) in the OA but a similar relationship was not observed for the YA for Step2 $Velocity_{AP}$ and $Velocity_{ML}$ values (Table 1). The OA appeared to reduce the rate of forward progression to complete the task of safely walking to the end of the platform.

A statistically significant ($p < 0.05$) Age × Direction interaction effect was observed for the spatial parameters step width and length in Step2, which is in contrast to the observations stated above for Step1, an unperturbed step. Consistent with findings observed for Step2 velocity, post hoc analyses revealed that OA did not alter step width as a result of the perturbation; this is in contrast to response generated by YA who increased Step2 width in response to the perturbation. The observed interaction effect for Step2 width therefore appeared to be driven by the response of the YA, who significantly increased their step width ($p < 0.05$) in the forward perturbation trials compared to the posterior 'catch' perturbation trials.

For the Step2 length, post hoc analyses to explore the observed interaction effects further revealed a significant ($p < 0.05$) reduction in the step length generated by OA following forward perturbations (Fig. 2A). We conducted an additional examination of the data to further examine these observations using descriptive statistics (mean, standard deviation, etc.). This analysis revealed that a high degree of variability in the forward perturbation responses for OA: both negative and positive step lengths were generated, these were not participant specific, in fact some individuals generated *both* step responses (Fig. 2B). Upon careful inspection of the data it appeared that when the postural responses were pooled by direction (positive or negative Step2 length), 54% of OA responses where posteriorly directed (25 of 46 trials). Note that this observation highlights both inter and intra subject variability within the older adult participants; it is important to note that this negative Step2 length was not observed in the YA data set in any trial or perturbation direction.

In an effort to explore the nature of these variable forward/backwards steps in more detail, two Pearson correlation analyses were

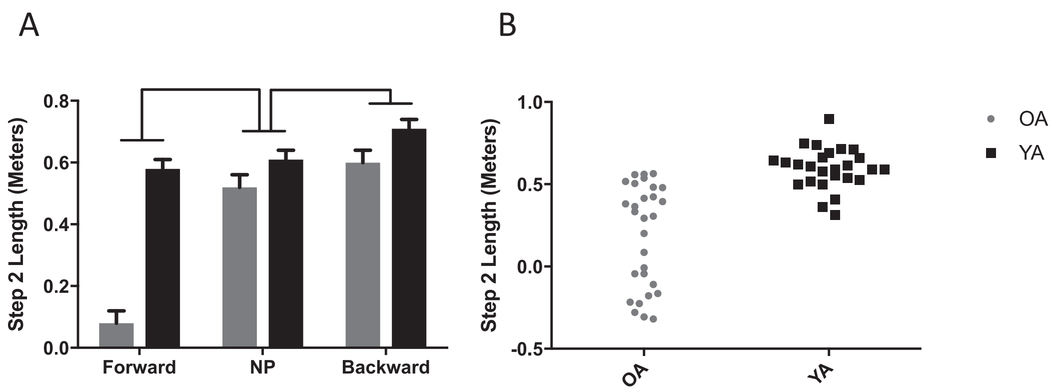

Fig. 2. A Step length (meters; mean ± standard error) for the second step following a perturbation (Step2) for YA (black bars) and OA (grey bars). We observed a statistically significant Age*Direction interaction effect ($p < 0.05$), as indicated by the black bars. Post-hoc analyses indicated that OA reduced their step length in particular for forward perturbations. To explore this finding in greater depth, Fig. 1B illustrates the distribution of forwards and backwards step lengths taken by OA and YA following forward perturbations; note that each point represents a single trial.

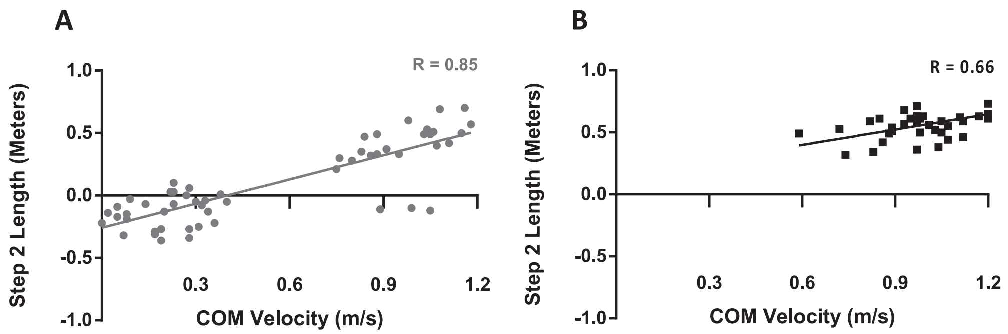

Fig. 3. Pearson correlation (R) values between instantaneous COM $velocity_{AP}$ (m/s) and step length (m) for OA (grey; Fig. 3A) and YA (black; Fig. 3B) in the second step following the forward perturbation; Step2. Step2 COM $velocity_{AP}$ was a strong predictive measure for Step2 length immediately following the forward perturbation for both OA and YA ($p > 0.05$). Older adults who generated positive Step2 length walked at a faster velocity (right cluster of points; Fig. 3A) while older adults who walked slower took more negative step lengths (left cluster of points in Fig. 3A). A negative Step2 length represents a backward directed step.

conducted one for each Age group. Both analyses were found to be significant ($p < 0.05$) and interestingly, these analyses revealed that Step2 $velocity_{AP}$ was strongly related to Step2 length for OA (R = 0.85; Fig. 3A) though a more moderate relationship was present between these variables for the YA (R = 0.66; Fig. 3B). This analysis revealed that OA who walked slower took more backwards steps following a perturbation while those who walked relatively faster see took more forward steps; see Fig. 3A for an illustration of this interesting finding (Fig. 3A).

4. Discussion

The present study was unique as participants were asked to complete a GI task, which is an inherently destabilizing task, while concurrently responding to an unpredictable forward directed platform perturbation. In general, OA appeared to initiate gait using a different strategy compared to YA. Without the presence of a perturbation, OA walked slower and took shorter steps. Following a forward perturbation, OA had increased difficulty attenuating the perturbation, as compared to YA, using a variable recovery strategy, possibly through a process mediated by augmenting $velocity_{AP.}$

4.1. Alterations in unperturbed GI

As hypothesized, OA initiated gait with reduced $velocity_{AP}$ and shorter step length as has been previously observed (Mbourou et al., 2003). Mbourou et al. (2003) observed that OA initiated gait significantly shorter than YA, additionally, the OA tested in that study were categorized into 'fallers' and 'non-fallers' based on both Berg Balance Scale score and the presence of a previously existing fall. They observed that the presence of a previous fall was associated with even shorter and more variable first step length (Mbourou et al., 2003). A limitation in the present study was not recording the number of previous falls or if a fall had occurred in any of the healthy community dwelling OA tested. Previously published papers that have focused on GI tasks in an OA population have focused on quantifying alterations in anticipatory postural adjustments (APA) using either data derived from electromyography (Brunt, Santos, Kim, Light, & Levy, 2005; Mickelborough et al., 2004; Polcyn, Lipsitz, Kerrigan, & Collins, 1998) or kinetic data (Halliday, Winter, Frank, Patla, & Prince, 1998; Henriksson & Hirschfeld, 2005), as opposed to the purely kinematic measures quantified in the present study. In the current study, two force plates were used only to trigger perturbation onset. Alterations in APAs were not associated with the primary research questions we wanted to address in this paper, which was to characterize age related changes in reactive stability following a support surface perturbation.

4.2. Age related alterations in recovery strategy following forward perturbations

Our secondary hypothesis focused on the increased challenge presented to OA following a forward perturbation issued during a GI task. This hypothesis was confirmed in that OA significantly reduced their Step2 $velocity_{AP}$, step length and step width as compared to YA following a forward perturbation. These results were similar to other studies, which have examined responses to forward perturbations in OA (Maki & McIlroy, 2006; McIntosh et al., 2017). Prior work has delivered a perturbation of the support surface during quiet stance or while stepping in place (e.g. Maki & McIlroy, 2006). In this earlier work only modest differences in terms of spatial and temporal measures of gait were observed; temporal measures represented the time to foot contact and not the time of the first step, due to being a non-dynamic task. As well the spatial parameters quantify the size of the step evoked by the perturbation, and not a step during continuous gait. In the present study, subjects were required to attenuate the effects of the perturbation while simultaneously attending to a transient goal oriented GI task. Therefore, alterations in spatial and temporal elements of gait, reflect an adopted strategy due to the perturbation during a difficult and dynamic task. It is possible that the more drastic age related differences observed in our study reflect the changes to motor control strategy which occur when combining the proactive requirements of the GI task and the reactive response following the perturbation.

Due to the specific and dynamic nature of our experimental design, results by McIntosh et al. (2017) are much more comparable, although perturbations issued in that protocol occurred during the on-going gait cycle, and not immediately following GI. The results of McIntosh et al. (2017) were collapsed across perturbation directions (left, right, forward, backwards), however many of the general trends in the present study were still consistent with those in this previous paper. In general, McIntosh et al. (2017) found that OA walked with a reduced Step2 velocity$_{AP}$, and had greater difficulty increasing the size of the BOS; with reduced step width and length. Interestingly these researchers also noted that OA tended to reduce Step2 length relative to pre-perturbation Step1 length. The capacity to increase the size of the BOS is imperative in the successful recovery to a perturbation (McIlroy and Maki, 1996; Maki & McIlroy, 2006). It would seem that OA are placing their foot down rapidly (shorter Step2 swing time), possible in an attempt to decrease the amount of time in single support (Maki & McIlroy, 2006), instead of taking the additional time to careful place the swing limb and increase the size of the BOS. This strategy has been reported before in OA. In the past, researchers proposed that this response may have a reduced energy requirement, which is important in OA who, due to the natural aging process, may have reduced muscle strength and power (Maki & McIlroy, 2006).

4.3. Variability in OA motor control strategy following forward perturbations

The OA in the present study had a tendency to take both a forward and backwards directed steps in the step following forward perturbation (Step2). Other studies have observed a similar response in the unperturbed trail limb (Marigold, Bethune, & Patla, 2003; Moyer et al., 2009). Moyer et al. (2009) utilized a contaminated surface (treated with glycerol) to simulate a trip; the results of this study noted equal proportions of backwards steps in older and YA. However, the alteration in the nature of the perturbation applied (robotic platform versus contaminated floor surface) as well as a difference in the age of the older adult participants (~76 years versus < 67 years of age) between the studies, could speak why we observed different stepping responses between the young and OA in our study. Researchers Moyer et al. (2009) suggested that the trail limb response was only observed in trials which seemed to be the most destabilizing for participants. The present study did not observe any backwards steps for any of the YA participants. Marigold et al. (2003) found that YA had a tendency to have a toe-tap response; consisting of touching the floor with the toe for a single instance beside the perturbed limb for their study which issued a perturbation via rollers under the foot. In this latter study, perturbations were limited to occur in the AP direction at heel contact, subjects however were unaware as to if a trial would contain a perturbation. Interestingly, this toe-tap response was only seen in first exposure trials in 60% of YA (Marigold et al., 2003). Marigold et al. (2003) reasoned that understanding trail limb responses is imperative, as successful recovery from an unexpected perturbation requires a quick response; the approximate onset of this response is just as the unperturbed limb is unloaded and initiating swing. A combination of these two trail limb responses were observed within the OA response trials in the present study.

It is possible that the inherent variability of OA during our GI task could explain the series of different responses reported within this population (Mbourou et al., 2003). Variability in GI strategy was noted by Mbourou et al. (2003) who found that OA with a previous history of falls initiated gait with a variable length in their first step, this pattern was not observed in OA without a known fall history or in YA. It is difficult in understand the singular purpose in coordinated human movement when the whole body has so many degrees of freedom (Muratori, Lamberg, Quinn, & Duff, 2013). Due to the multi-segmented nature of the human body there is a near unlimited number of combinations of motion about these joints (Muratori et al., 2013; Oullier, Bennett, & Newell, 2005). In theory the human movement command center integrates together the local constraints (velocity, forces etc.), the participant and the task, in order to generate a movement which is 'stabilizing' and optimal for the individuals needs. A series of studies were presented in a review by Oullier et al. (2005), many of which observed biphasic distribution in coordinated postural strategies, similar to the results reported in the present study. However, we would argue that there is still very little known about the shift in coordination from one strategy to the next. When we observe deviations from the expected movement, in this case that pattern consistently produced by the young adult participants, we could conjecture as to the purpose to these behaviors in the OA population. Secondary correlation analyses revealed that the reduced Step2 velocity$_{AP}$ was strongly related the occurrence of a forward or backwards directed step. Specifically, a slower velocity was strongly related to posterior stepping strategies. The importance of velocity$_{AP}$ has been previously observed in GI to be correlated to mediolateral instabilities (Caderby et al., 2014). In healthy YA, reduced velocity$_{AP}$ was associated with a higher prevalence of mediolateral instabilities, due to a reduction in the size of the anticipatory postural adjustment which is required to propel the body forward (Caderby et al., 2014). It is important to consider that velocity$_{AP}$ was variable in OA trial-to-trial, as the pattern of backwards or forward steps were observed both within and between subjects. Future analyses could be performed to consider why OA are variable in selection of GI velocity. Additional studies have observed a lack or forward momentum in OA during a GI task (Polcyn et al., 1998). It is not without precedent that OA initiate gait with a reduction in forward momentum and thereby velocity, it is however difficult to ascertain if this strategy poses a potential risk.

Previous studies have observed alterations in velocity$_{AP}$ as a mechanism to control the body following an external perturbation. McAndrew, Dingwell, and Wilken (2010) elicited a combined visual and sinusoidal perturbation during a dynamic treadmill walking task. These researchers observed that healthy YA adopted spatial and temporal measures of gait as a control strategy to attenuate the destabilizing and difficult perturbations (McAndrew et al., 2010). The subjects increased gait variability in terms of step length and velocity in perturbation trials relative to NP trails (McAndrew et al., 2010). The perturbations in this study by McAndrew et al. (2010) are likely more difficult that those utilized in the present study. It is possible that the OA in the present study, increased variability also as a control strategy. This was done by altering spatial and temporal measures of gait in an effort to attenuate the perturbations which they found to be heavily destabilizing.

4.4. Limitations

One limitation of the current study is the unequal number of forward and backward perturbations. This design permitted capturing *reactive* stepping responses for the larger experimental objectives and also reduced the possibility of learning/practice responses while limiting fatigue in participants, especially OA. Future experiments will ensure a more balanced trial presentation and will focus on differences in stepping in a lower mobility OA population as we acknowledge that our OA population were relatively healthy. Additionally, it is difficult in the present study to make the argument whether or not the series of strategies used by in the OA following forward perturbations reduce, or conversely, increase the risk of falling. All responses to perturbations were 'successful' in that no falls were observed. However, unlike perturbations generated by a robotic platform, during an unconstrained *real-life* slip there is no deceleration phase. Previous work has revealed that the platform deceleration produces a secondary response (due to the generation of forces opposite to the original destabilizing acceleration of the platform; McIlroy & Maki, 1994). In an a more ecological situation (e.g. wet floor at supermarket) it is possible the lead foot could continue to slip and the resulting backwards directed step may not be stabilizing, resulting in a posterior fall.

5. Conclusion

In the present study, OA demonstrated an altered GI profile relative to the YA following an AP perturbation to the support surface. Specifically, OA chose to initiate gait with a reduced velocity_{AP} and walk with a more narrowed and shortened BOS due to short step length and width. Following a translation of the support surface, the recovery method used by OA was more variable than those used by the YA. For example, in some trials OA stepped posteriorly following the perturbation; given the nature of the goal-directed, GI task, this finding was somewhat unexpected. It is difficult to determine what, if any, factor (e.g. stability) was being optimized by OA in producing this postural control strategy. However, correlational analysis did reveal that the reduced, and variable forward velocity was predictive of the direction of the step (either forward or backwards). Future work will continue analyzing the effect of difficult and transient locomotor activities and on modulating and training responses to reduce or modify fall risk.

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Conflict of interest

The authors have no conflict of interest to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2018.11.008.

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