Body configuration as a predictor of centre of mass displacement in a forward reactive step

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ABSTRACT

In balance perturbations that elicit backwards reactive steps, body configuration at stepping contact is related to likelihood of balance recovery. However, less is known about the relationship between body configuration (at stepping contact) and underlying centre of mass (COM) dynamics during dynamic perturbations requiring a forward reactive step. Accordingly, the primary objective of this study was to characterize the potential relationships between body configuration and COM displacement during simulated trips. Towards determining the robustness of these relationships, trips were simulated in both baseline and increased passive joint stiffness conditions. Sixteen healthy adults participated in this study. Trips were simulated using a tether release paradigm where participants were suddenly released, necessitating a forward step (onto a force plate) to recover their balance. Trials were performed in a baseline unconstrained condition, and in a 'corset' condition to increase passive stiffness of the trunk and hips. In all trials, whole body kinematics and kinetics were collected. Multiple linear regression models were run to assess the relationship of body angles to COM displacement in both the anteroposterior (AP) and mediolateral (ML) planes. Regression models showed a significant association of sagittal plane body configuration to both COM displacement at stepping contact and maximum COM displacement in the AP plane. Across models, the strongest predictor was the trail leg angle. Associations were stronger in the increased passive stiffness condition (average $R^2 = 0.366$) compared to the baseline condition (average $R^2 = 0.266$). Poor association of body configuration to COM displacement was found in the ML plane. The significant associations observed between body configuration and COM dynamics in simulated trips supports the potential downstream application of these models in identifying individuals with impaired balance control and increased fall risk.

1. Introduction

Falls are a leading cause of injury in society. For example, falls have been identified as the most common cause of hospitalized treatment, emergency room visits, permanent partial disability and permanent total disability, with an associated cost of over $8 billion in Canada alone (Parachute, 2015). Falling can greatly affect health outcomes as resultant injuries can lead to increased morbidity and mortality (Bhattacharya, Maung, Schuster, & Davis, 2016; Katsoulis et al., 2017; Papadimitriou & Perry, 2017). Aging can impair the ability to maintain stability, and thus increase the risk of experiencing a fall (Maki & McIlroy, 2006; McIlroy & Maki,

1996; O'Loughlin, Robitaille, Boivin, & Suissa, 1993). There is also a greater susceptibility to injury from a fall in aging due to frailty and other conditions, such as osteoporosis, which are more common in later stages of life (Anagnostis et al., 2009). Towards attenuating the grave implications of falls on health outcomes, protective mechanisms to regain balance in a perturbation should be investigated.

A primary strategy to regain balance is a reactive step (Hsiao & Robinovitch, 1997; Maki, McIlroy, & Perry, 1996; Nashner, 1980) to preserve centre of mass (COM) position within the boundaries of the base of support (BOS) (Hof, Gazendam, & Sinke, 2005; Shumway-Cook & Woollacott, 1995; Winter, 1995a). In particular, reactive stepping strategy has been noted in 42% of falls observed in long-term care (Yang, Schonnop, Feldman, & Robinovitch, 2013) where trips are the leading cause of falls (Robinovitch et al., 2013). Upon a loss of balance, a reactive step expands the BOS to contain the COM with the goal of preventing an impending fall. Various factors are related to whether a reactive step is successful such as step length, step execution time and stepping leg force generated (Hsiao & Robinovitch, 1999; Maki et al., 1996; Singer, Prentice, & McIlroy, 2016). With an identified relationship of step length to successful step recovery, body configuration used to produce a reactive step remains an important consideration in assessing fall risk.

Body configuration is a critical determinant of success during perturbations that simulate backwards loss of balance. For example, successful balance recovery (vs. falling) was associated with increased trunk flexion (which moves the COM anterior) and hip extension of the stepping leg (which serves to increase the posterior base of support boundary) (Weerdesteyn, Laing, & Robinovitch, 2012). Furthermore, Hsiao and Robinovitch (2001) found that mechanical advantage, defined as stepping angle divided by body lean angle at stepping contact, was associated with older adults taking single vs. multiple steps in response to backwards perturbations. Given their mechanistic importance in maintaining balance in a backward perturbation, sagittal plane joint angles may relate to balance outcomes in trips (forward perturbations). If an association exists between sagittal plane joint angles and factors related to balance recovery outcomes in a forward perturbation, controlling sagittal plane angles could serve as the focus of interventions to improve reactive balance control, or act as baseline and post-intervention indicators of reactive balance control abilities.

When assessing a relationship of body configuration to measures related to balance recovery the effect of increased trunk stiffness, as seen in an aging population (Allum, Carpenter, Honegger, Adkin, & Bloem, 2002; Rietdyk, Patla, Winter, Ishac, & Little, 1999), should be considered. Increased trunk stiffness can compromise stepping efficiency as it interferes with early compensatory movement to minimize COM displacement in a reactive step (Allum et al., 2002; Rietdyk et al., 1999). This effect of trunk stiffness likely contributes to changes in reactive stepping across the lifespan (Grabiner et al., 2008), where in particular, older adults having lower stepping efficiency (Luchies, Alexander, Schultz, & Ashton-Miller, 1994; Thelen et al., 2000; Thelen, Wojcik, Schultz, Ashton-Miller, & Alexander, 1997). The effect of increased trunk stiffness on stepping responses is also of interest to individuals with degenerative disorders such as osteoarthritis and hyperkyphosis (Nodehi-moghadam, Taghipour, & Alibazi, 2014), Parkinson's disease (Carpenter, Allum, Honegger, Adkin, & Bloem, 2004) and patients with a total leg proprioceptive loss (Bloem, Allum, Carpenter, Verschuuren, & Honegger, 2002). To simulate higher joint stiffness seen in aging and clinical populations a corset has been used to passively increase trunk and hip stiffness of participants (Grüneberg, Bloem, Honegger, & Allum, 2004; Van der Burg, Pijnappels, & van Dieen, 2007). Use of a corset has been shown to direct trunk movement in the direction of the impending fall in a medial-lateral perturbation (Grüneberg et al., 2004) which is consistent with trunk motion observed in older adults (Allum et al., 2002). Building from previous literature, the imposition of increased passive stiffness to the hips and trunk may have the effects of restricting range of motion, decreasing step efficacy, and inducing greater variability in balance recovery strategies and ultimate COM movement. Therefore, investigating the ability of body configuration to predict dynamic balance control responses across joint stiffness conditions would increase the robustness of study findings by probing the influence of stiffness in isolation of other effects of aging.

The primary objective of this study was to investigate whether body configuration at stepping contact, which has previously been shown to predict balance recovery during backwards perturbations (Hsiao & Robinovitch, 2001; Weerdesteyn et al., 2012), was associated with COM dynamics during forward balance perturbations. If such a relationship exists, there is opportunity to evaluate fall risk in simulated trips based on body configuration when COM position cannot be robustly measured. Two categories of predictive models were assessed including: i) a 'simple' model as reported by Weerdesteyn et al. (2012) including only leg and trunk angles; and ii) a comprehensive model that included leg, trunk, knee and hip angles. To assess the robustness of these relationships, reactive control trials including both baseline and increased passive stiffness conditions were employed with the latter intended to simulate the higher trunk stiffness reported for older adults and clinical populations. Our first hypothesis was that the body configuration models would be significantly associated with anteroposterior (AP) COM displacement at stepping contact and maximum AP COM displacement. Our second hypothesis was that the comprehensive model would substantially increase the strength of the association, defined as increase in $R^2 > 0.1$. Our third hypothesis was that the associations would be weaker in the increased stiffness condition (due to a decrease in range of motion resulting in greater variability in COM displacement) defined as a decrease in $R^2 > 0.1$. A secondary study objective was to assess the relationship between these models on mediolateral (ML) COM displacement. Based on limited previous work modeling these relationships in the ML plane, we had no *a priori* hypothesis for this objective.

2. Methods

2.1. Participant characteristics

Sixteen healthy young adults (eight females) participated in this study (mean (SD) age, height, and body mass were 22.5 (2.5) years, 1.70 (0.10) m, and 68.4 (9.7) kg, respectively). All participants were free of any injuries or health issues with the potential to influence balance control. Informed consent was obtained from all participants, and the study protocol was approved by the Office of

Fig. 1. Lean angle prior to tether release with 15% of body weight supported by the tether.

Research Ethics at the University of Waterloo.

2.2. Instrumentation

A 3-dimensional motion capture system (Optotrak Certus, Northern Digital Incorporated, Waterloo, ON, Canada) and a force platform (OR6-7, Advanced Mechanical Technology Incorporated, Watertown, MA, USA) were used to acquire whole body kinematics (100 Hz) and step kinetics (2000 Hz) respectively. An 11-segment kinematic model was generated using rigid clusters of four markers placed on the feet and thighs bilaterally, that were digitized to give the position of the toe tips, lateral malleolus, medial malleolus, calcaneous, lateral condyles, medial condyles and greater trochanters. Individual markers were placed bilaterally on the acromion, lateral epicondyle and ulnar styloid. In the increased passive stiffness condition an additional marker was attached to the plastic corset.

2.3. Experimental protocol

A tether release paradigm was used to incite a forward loss of balance. This experimental paradigm has been used in a number of past studies to incite a loss of balance in the forward, backward and lateral directions (Do, Breniere, & Brenguier, 1982; Hoshiyama, 1993; Hsiao & Robinovitch, 1999, 2001; Singer et al., 2016; Thelen et al., 1997; Wojcik, Thelen, Schultz, Ashton-Miller, & Alexander, 1999). Specifically, participants began tethered to a rigid steel support base using an electromagnet via adjustable cables attached to the left and right ilium. Each cable was placed in series with a load cell to monitor tether force at 2000 Hz (MLP-300-CO, Transducer Techniques, Temecula, CA, USA). Participants were instructed to adopt an initial anterior lean angle such that a target of 15% body weight was supported by the electromagnet as measured by the load cells. Participants achieved this lean angle by rotating about the ankle joint while maintaining a neutral posture in the knees and hips while arms were folded across the chest (Fig. 1). Posthoc analysis demonstrated the targeting protocol was effective, with a mean (SD) body weight support of 14.7 (0.5)% across all participants and trials. The tethers were randomly released in tandem inducing a forward balance perturbation onto the in-ground force plate. Participants were instructed to regain balance using a single reactive step where the stepping foot landed on the force plate. No instruction was given on what leg to use in the reactive step.

The balance perturbations were conducted in two conditions; a baseline and an increased passive stiffness condition. Participants underwent 5 tether releases in both the baseline and increased passive stiffness conditions. The order of conditions was block randomized so half of the participants began with the baseline condition, and vice versa.

In the increased passive stiffness condition a plastic corset was worn which crossed the hips to limit motion of the hip and trunk (Fig. 2). Comparing the baseline to increased passive stiffness conditions, the corset significantly attenuated maximum passive trunk flexion angle from 82.9 (15.3) degrees in the baseline condition to 38.3 (11.5) degrees in the increased passive stiffness condition ($p < 0.001$).

2.4. Data analysis

Using custom Matlab software (R2016b, The Mathworks Inc., Natick, Massachusetts, USA) gaps in kinematic data less than 200 ms were interpolated using a cubic spline, consistent with best practice (Howarth & Callaghan, 2010). Both kinematic and force

Fig. 2. Participant wearing plastic corset to passively increase hip and trunk stiffness from the anterior (left) and posterior (right) views.

plate data were filtered using a second-order, dual-pass Butterworth filter with effective cut offs of 6 and 50 Hz for kinematic and force data, respectively. In each trial whole body COM position was calculated in both the AP and ML directions based on an 11-segment rigid link model (Winter, 2009).

Leg and trunk angles were calculated at stepping contact (SC) in both the sagittal and frontal planes. Leg angle was defined between the vertical and a vector connecting the greater trochanter to calcaneous. Trunk angle was defined between the vertical and a vector connecting the mid-point between the greater trochanters to the mid-point between the left and right acromion (Fig. 3). Sagittal and frontal knee and hip angles were defined as the angle between the distal segment and proximal segment in the plane of interest. SC was defined as the first time point where the vertical ground reaction force exceeded 10 N on the force plate.

COM displacement was calculated at both SC and for the maximal COM displacement over the course of the trial in the AP and ML directions. The displacement was the difference in mean COM position in the 2 s prior to tether release to COM position at the aforementioned time points. Participants were stationary in the 2 s prior to tether release while the tether supported the target of 15% of body weight.

2.5. Statistical analysis

Forced entry multiple regression models were run to determine if body configuration was associated with COM displacement at SC (D_{step}) and maximum COM displacement (D_{max}) in the AP and ML directions for both baseline and increased passive stiffness conditions. Two plane-specific regression models were run for each condition: i) a simple model where only step leg, trail leg and trunk angles were input as predictors; and ii) a comprehensive model which built on the simple model by including bilateral hip and knee angles in addition to step leg, trail leg and trunk angles. In each of the simple and comprehensive models, all variables listed above were input as predictors regardless of strength of association to the dependent measure. As there were always more predictor variables included in the comprehensive (7) versus simple models (3), we evaluated model strength using adjusted R^2 values which account for potential collinearity between predictor variables. Our a priori framework for model strength employed an adjusted $R^2 > 0.5$ as strong, R^2 between 0.25 and 0.5 as moderate, and $R^2 < 0.25$ as weak (Mukaka, 2012). An adjusted $R^2 > 0.1$ represented a clinically significant difference between the predictive capacity of the comprehensive and simple regression models. All
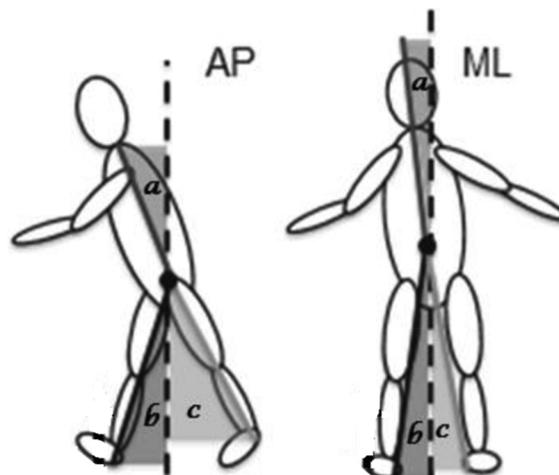

Fig. 3. **a** represents a positive trunk angle. **b** represents a positive stepping leg angle. **c** represents a positive trail leg angle.

Table 1

Forced entry multiple regression model summaries of body configuration to COM displacement. Significant predictors ($p < 0.05$) are listed with their unstandardized B coefficient for model constants and β coefficient for significant predictors respectively. Model summary results are expressed as adjusted R^2, F and p values.

Plane	Stiffness Condition	Model Type	COM at SC (D_{step})	Max. COM after SC (D_{max})
AP	Baseline	Comprehensive	Trail Leg (β = 0.534) $R^2 = 0.244$; F = 4.37; $p < 0.001$	Step Leg (β = -0.847), Trail Leg (β = 0.855), Step Hip (β = -2.115) and Step Knee (β = -0.855) $R^2 = 0.388$; F = 7.60; $p < 0.001$
		Simple	Trail Leg (β = 0.378) $R^2 = 0.148$; F = 5.23; $p = 0.003$	Trail Leg (β = 0.473) and Step Leg (β = -0.245) $R^2 = 0.287$; F = 10.78; $p < 0.001$
	Increased Passive Stiffness	Comprehensive	Trail Leg (β = 0.571) $R^2 = 0.317$; F = 6.09; $p < 0.001$	Constant (B = -238.51), Trail Leg (β = 0.980) $R^2 = 0.543$; F = 14.08; $p < 0.001$
		Simple	Trail Leg (β = 0.474) $R^2 = 0.187$; F = 6.90; $p < 0.001$	Constant (B = -177.93), Trail Leg (β = 0.629), Step Leg (β = 0.260) and Trunk (β = 0.230) $R^2 = 0.417$; F = 19.34; $p < 0.001$
ML	Baseline	Comprehensive	Constant (B = 23.60), None $R^2 = 0.028$; F = 1.30; $p = 0.262$	Constant (B = 88.43), Trail Leg (β = -0.623) $R^2 = 0.240$; F = 4.29; $p = 0.001$
		Simple	Constant (B = 82.04), None $R^2 = 0.017$; F = 1.42; $p = 0.243$	Constant (B = 15.70), Trail Leg (β = -0.524) $R^2 = 0.255$; F = 9.30; $p < 0.001$
	Increased Passive Stiffness	Comprehensive	Constant (B = 20.41) $R^2 = 0.123$; F = 2.54; $p = 0.022$	Constant (B = 136.39), Trail Knee (β = 0.953) and Trail Leg (β = -1.371) $R^2 = 0.208$; F = 3.88; $p = 0.001$
		Simple	Constant (B = 77.14) $R^2 = 0.052$; F = 2.40; $p = 0.075$	Constant (B = 28.93) $R^2 = 0.033$; F = 1.87; $p = 0.141$

[1] R^2 values represent the variance explained by the combined effects of all predictor variables included, even if only a subset emerged as significant.

[2] Constants (i.e. y-intercepts) are only presented for cases in which they emerged as significant factors.

Fig. 4. Simple correlation of sagittal trail leg angle to maximum AP COM displacement in the increased passive stiffness condition.

statistical analyses were performed in SPSS (IBM SPSS Statistics, Version 22.0, Armonk, NY, U.S.A.).

3. Results

AP body configuration was significantly associated with COM position during dynamic reactive stepping. In the baseline stiffness condition significant amounts of variance were explained by the simple and comprehensive models for AP D_{step} ($R^2 = 0.148$ and $R^2 = 0.244$, respectively) and AP D_{max} ($R^2 = 0.287$ and $R^2 = 0.388$, respectively) (Table 1). Sagittal trail leg angle was the most robust independent variable as it was a significant positive predictor of both AP D_{step} and AP D_{max}. Step leg angle also emerged as a significant negative predictor for AP D_{max}. Model improvement by the comprehensive model was clinically significant for AP D_{max} (R^2 difference = 0.101), which was attributed to step limb hip and knee angle contributions. The comprehensive model provided limited clinical improvement for AP D_{step}.

In the increased passive stiffness condition for the AP direction, sagittal trail leg angle remained the most robust independent variable where significant amounts of variance were explained by the simple and comprehensive models for AP D_{step} ($R^2 = 0.148$ and $R^2 = 0.244$, respectively) and AP D_{max} ($R^2 = 0.0287$ and $R^2 = 0.388$, respectively) (Table 1). Similar to the baseline stiffness condition, trail leg angle was the only variable significantly associated with AP D_{step}, with this relationship being positively correlated. AP D_{max} was significantly positively associated with trail and step leg angle. Trunk angle also emerged as a significant factor and was positively associated with AP D_{max}. The greater variance explained by the comprehensive model was clinically significant for both AP D_{step} (R^2 difference = 0.130), and AP D_{max} (R^2 difference = 0.126). The comprehensive models demonstrated moderate and strong associations to AP D_{step} and AP D_{max} respectively, which decrease to weak and moderate associations in the simple model. As in the baseline condition, the sagittal trail leg angle was a significant positive predictor in all models. Even on its own, Fig. 4 illustrates the ability of this robust variable to predict AP D_{max} in the increased stiffness condition.

In the ML plane, there was no association between ML body configuration and ML D_{step} in either the baseline or passive stiffness conditions (Table 1). For ML D_{max}, trail leg angle was a significant negative predictor in the baseline stiffness condition, and no additional value was provided by the comprehensive model. In the increased stiffness condition, the simple model was not associated with ML D_{max}, but the comprehensive model (including a positive association of trail knee angle, and negative association of trail leg angle) was associated with ML D_{max} and explained 20.8% of the variance.

In the AP direction the increased passive stiffness regression models had stronger associations to AP D_{step} and D_{max} across both simple and comprehensive models. In the ML direction the association of comprehensive and simple models to ML D_{max} were stronger in the baseline condition.

4. Discussion

The primary objective of this study was to determine whether body configuration at stepping contact was associated with COM dynamics during forward balance perturbations (i.e. that required a forward step). In support of hypothesis one, all AP predictive models showed a significant association with COM displacement which tended to be driven by trail leg angle as the primary predictor. In support of hypothesis two, a clinically significant increase in variance explained in the comprehensive compared to simple model in the AP direction was observed across all model conditions except to centre of mass displacement at stepping contact (D_{step}) in the baseline stiffness condition. In contrast to our third hypothesis, regression models for the AP plane showed stronger association in the increased vs. baseline passive stiffness conditions (Comprehensive D_{max} $R^2 = 0.543$ vs. 0.388; Simple D_{max} $R^2 = 0.417$ vs. 0.287, respectively). Finally, we observed only poor associations between ML body configuration and ML COM displacement during forward balance perturbations. Overall, this study adds to the literature by demonstrating that body configuration (predominantly driven by trail leg angle) is associated with AP COM displacement dynamics during forward reactive stepping. Practically, this study supports the potential to evaluate fall risk in a simulated trip based on the body configuration at stepping contact.

The significant sagittal plane associations between body configuration and D_{max} support that the proposed statistical model may have clinical utility to assess risk of a fall in a trip. As the variance explained by the models was greater in the increased stiffness condition, this approach may be more predictive for populations that have higher stiffness including older adults (Allum et al., 2002; Rietdyk et al., 1999). The higher potential for clinical application in older adults is beneficial as they are at increased risk of falling (Maki & McIlroy, 2006; McIlroy & Maki, 1996; O'Loughlin et al., 1993) with the most common cause of falls being trips (Robinovitch et al., 2013). Finally, the stronger associations between body configuration and D_{max} (compared to D_{step}) provide a better clinical relationship for application. A loss of balance occurs when the COM displaces outside of the BOS (Hof et al., 2005; Shumway-Cook & Woollacott, 1995; Winter, 1995a) and so the time of D_{max} is when there is the greatest associated fall risk.

Considering the associations of sagittal body configuration to AP COM displacement, trail and trunk angles were both positively associated to COM displacement. In the forward reactive step, the body rotates about the trail leg until the step leg can plant the foot to restore balance. As the body is moving about the trail leg the greater the trail leg angle, the further the body will have displaced forward resulting in greater COM displacement. The positive association of trunk angle to COM displacement is attributed to a similar mechanism as in the forward balance perturbation the trunk will rotate forward about the hip increasing both the trunk angle and anterior COM displacement. When AP step leg angle was a significant predictor of COM displacement, the association was negative. This finding highlights that as step leg angle increases the risk of experiencing a fall is likely lower as there is less COM displacement and therefore less likelihood the COM will displace beyond the margin of stability. This finding is consistent with Weerdesteyn et al. (2012) as they observed that greater leg angles were associated with a greater probability of successful balance recovery.

The proposed statistical model does not have utility in the ML direction as the association of body configuration to COM displacement was weak across 7 of 8 combinations of conditions tested. The low predictive ability of both the simple and comprehensive models is likely driven by the direction of perturbation. The tether release incites a forward balance perturbation where the primary travel direction of the COM is anterior. The ML COM displacement is likely a byproduct of the body moving in the sagittal plane to achieve a successful reactive step where the greatest challenge to balance recovery is in the sagittal plane. As such, there was little association between body configuration and COM displacement in the ML direction.

Across the regression models analyzed, the trail leg was the strongest predictor of AP COM displacement in 7 of the 8 models, where in the 8th model it was the second strongest predictor. The importance of the trail leg to AP COM displacement is attributed to the body acting as an inverted pendulum about the trail leg foot upon tether release (Hof et al., 2005). Previous work has identified that the body acts as an inverted pendulum in walking where a voluntary forward loss of balance is created followed by a reactive step to propel the body forward (Winter, 1995b). In the increased passive stiffness condition, the external constraint of the corset constrains the body to act more like an inverted pendulum. The imposed passive stiffness reduces the number of motor solutions available to maintain balance, whereas unconstrained a participant would have an abundance of available motor solutions (Latash, 2012) which can be flexibly configured to maintain balance. This explains the greater variance explained in the increased passive stiffness condition as the corset restricts movement of the body to behave more like an inverted pendulum.

While this study demonstrates the efficacy of a statistical model inferring COM displacement in a simulated trip from body configuration at stepping contact, future work is required to support potential development of a clinical tool (or validation of an existing one). With a goal of identifying individuals who are at greater risk of a fall in a trip, future work should confirm that the association of body configuration to COM displacement exists in an aging population. Although the inclusion of an increased passive stiffness condition replicates one factor that compromises reactive stepping ability in older individuals, it does not consider all factors of the aging process that may relate to reactive stepping strategy. Furthermore, as perturbation intensity has been demonstrated to be a significant predictor of recovery outcomes (de Kam, Roelofs, Geurts, & Weerdesteyn, 2018), its effect on balance recovery in forward perturbations should be considered. Finally, future work should explore whether lower fidelity motion capture equipment (i.e. video cameras) can robustly infer COM displacement in a forward reactive step. Convolutional pose machines (Wei, Ramakrishna, Kanade, & Sheikh, 2016) are emerging as a technology that can robustly estimate two dimensional joint centre locations from video, which would allow for sagittal plane body angle calculations. These demonstrated advances in markerless motion tracking would allow better efficacy of a clinically applicable model.

Following future confirmatory work, the developed statistical models may have clinical applications as baseline measures of COM control. In particular, individuals that have greater D_{max} can be identified as at higher fall risk in a trip. This approach is more applicable than directly measuring COM position as body configuration can be measured using a single camera in the sagittal plane while calculating COM would be less reliable and have a higher associated computational cost with the same instrumentation. Additionally, by quantifying the body configuration at stepping contact a clinician can develop interventions targeted at addressing the body configuration used, where in particular there would be a goal to reduce trail leg angle to minimize COM displacement. While past work has demonstrated that perturbation-based balance training can improve reactive step quality (van Duijnhoven et al., 2018), by focusing training on controlling kinematic features related to COM displacement (i.e. trail leg angle) future training programs may be able to improve on past documented successes. Based on the results of this study clinicians can choose whether they prefer to use the comprehensive or simple models in application. The comprehensive regression models had stronger association to COM displacement than the simple counter parts but had higher associated computational costs. Although there was a difference in variance explained between model complexities, the simple model in the increased passive stiffness condition still explained greater than 40% of variance in the COM displacement measure, which may be acceptable for clinical use.

Although this study supports potential application of body configuration measures to gain insight into COM dynamics in a forward reactive step, the study design is not without limitations. First, each perturbation was considered independent and a potential learning effect may have affected performance. Additionally, the independent regression approach we employed did not account for potential within-participant variance. While additional analyses confirmed that general findings were not influenced by

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incorporating a repeated measures factor, it had the drawback of requiring participant-specific constant variables. Accordingly, towards providing generalizable predictive equations (Table 1), repeated measures factors were not included in the analyses. Secondly, we used an increased passive stiffness condition to replicate the stepping response of the clinical populations of interest opposed to recruiting from the clinical population. However, use of an artificial stiffness condition better tests model robustness as it directly influences body configuration and allowed us to investigate the effect of greater stiffness in isolation of other aging effects.

5. Conclusion

The use of sagittal body angles at stepping contact in a forward balance perturbation shows promise for predicting maximum AP COM displacement during a forward reactive step. This relationship proved to be strongest for conditions with increased passive stiffness to the hip and trunk, which mimics populations at greater fall risk including older adults and Parkinson disease patients. This work provides opportunity to assess likelihood of falling after a trip in clinical application via a baseline assessment, which can identify individuals with the highest fall risk based on maximum COM displacement.

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Declaration of Competing Interest

None.

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