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Keywords

Tau guidance; general tau theory; gait initiation; postural control; aging; falls

Abstract

Background. Prospective balance control can be assessed in terms of the characteristics of a tau-guidance function that summarizes the velocity profile of Centre of Pressure (CoP) movement during gait initiation. This allows the nature of CoP movement to be assessed on a continuum between controlled 'soft'- and unstable 'hard' CoP-motion gap-closure. Previous research has shown less stable movement patterns with harder closures with increasing age, which makes movements more prone to overshooting and could possibly explain the increasing falls risk with age.

Research questions. The primary research question was 'what is the relationship between falls incidence and tau-guidance in the mediolateral centre of pressure movements during gait initiation?' The secondary research question was 'what are the influences of age and task demands on the variability of tau-guidance characteristics?'.

Methods. Sixteen young adults and 76 older adults performed 33 gait initiations from a force platform, stepping onto stepping-targets imposing differing task demands. Older participants completed a one-year follow-up screening for falls. An analysis was performed investigating linear relationships between a tau-guidance function and the time-to-closure (tau) of the mediolateral centre of pressure motion-gap with coupling constant *K* (dependent variable). **Results.** Gait-related falls during the 12-month follow-up period were associated with higher tau-*K* values. Furthermore, longer movement preparation time was associated with lower *K* values, particularly in fallers. Previously-reported age-related increases of the tau-coupling constant values which were found in studies of unconstrained gait initiation were not present in our results.

Significance. The presence of the targeting task provided a more prescriptive environment compared to unconstrained gait initiation and could explain the absence of age-related changes to the produced *K* values. Falls incidence was found to be associated with higher values of *K*, indicating less stable movement. Future studies should investigate the practical implications of these findings for falls prevention.

Introduction

In light of the increasing number of older adults globally, falling has become one of the major problems faced by society. For older adults, falling leads to injury, decreases in quality of life and potentially even death [1]. Furthermore, falling is a major burden on society in terms of medical costs [2,3]. Given this relevance, it is important to further investigate the mechanisms behind falling and the deficits in motor control that are associated with these incidents. Falls have been associated with age-related declines of the postural system [4,5] and the vast majority are reported to occur during gait [6]. It is known that the way in which gait is initiated changes with age [7]. The current study therefore, focusses on dynamic balance during gait initiation to better understand the mechanisms behind falling.

The characteristics of closing motion gaps (i.e. the gap between a current state of the system and a goal state) can be described in terms of the relationship between the time-to-closure (tau) of the movement gap and a tau-guidance function (τ_G) [8–10]. Such an approach has been shown to accurately describe the closing of motion gaps in numerous natural movements, such as club movements in golf putting strokes [11], frequency glides in singing [9] and infant suckling behaviour [12,13]. Similarly, in gait initiation, the mediolateral shift of the Centre of Pressure (CoP_x) when transferring weight onto one support leg can be conceived as a motion gap, and the control of its closure during gait initiation can be analyzed using the principles of tau-guidance [14–16]. Using an analysis of the change in tau during a movement (τ_{CoPx}), the velocity profile of the closure of the gap can be summarized and analyzed. By defining the linear relationship between the tau of the movement and a mathematical function τ_G, following the formula $\tau_{CoPx} = K * \tau_G$, the coupling constant *K* can be computed and represents the tau-guidance characteristics of the movement. In this formula, τ_G represents the mathematical description of the time to closure of a canonical energy gap (G(t)) that closes with a constant acceleration. By keeping the tau of the motion gap (τ_{CoPx}) in a constant relationship with τ_G, one can assure a smooth closure of the gap. As τ_G is based on a gap that closes with a constant acceleration, a *K* of 1 (or larger) is associated with a constantly accelerating movement. In postural movement, such a *K* would not be beneficial, as it indicates an accelerating closure of the gap and hence an overshooting of the movement, ultimately challenging the body's postural stability systems. A *K* between 0.5 and 1 would be indicative of a gap-closure with a significant deceleration phase at the end, and hence a hard contact, leading to potentially unstable CoP movements. A *K* value between 0 and 0.5 indicates zero-velocity at the end of the movement, with soft contact closure with the movement's end point, reflecting a stable CoP movement [8].

Spencer and Van der Meer [14] used an analysis of tau-guidance on mediolateral CoP trajectories during gait initiation. They showed that the coupling constant *K* in the postural movements increased from 0.40 for people in their 20s to 0.79 for people in their 80s. These results indicated that, with age, participants made harder contact when closing CoP_x motion-gaps in the initiation of gait. Harder contact in the closure of motion-gaps are considered to be less controlled, as they rely on a larger deceleration close to contact and potentially an overshoot of the CoP_x movement. When the goal state of the CoP_x movement is close to the limit of support (as in the movement of transferring from bipedal stance to stance on a single foot in gait initiation), such an overshoot could lead to a loss of balance. Spencer and Van der Meer reasoned that the age-related increase in *K* could be associated with the increasing falls risk that is evident in ageing populations [14]. These results are of great value to understanding the age-related changes in dynamic postural control. However, a definitive link between tau-guidance and falls incidence remains to be established. Further, since differences in tau-coupling have been reported between individuals, it seems unreasonable to assume that coupling constant *K* would be invariant between trials. Little is known about the relationship between the movement preparation time required to establish tau-coupling. The current study, therefore, aimed to investigate the relationship between the coupling constant *K* and (1) gait-initiation difficulty, (2) preparation time, (3) age and (4) falls incidence.

Methods

Participants. Sixteen young adults (aged between 19 and 33) and 76 older adults (aged between 61 and 85) agreed to participate in this study. The difference in group size between the older and younger participants was required to ensure a sufficiently large sample size in the group of fallers in order to be able to investigate the effects of falls incidence at the completion of a 12-month falls follow-up. Based on the statistic that about one in three older adults fall at least once a year [17], it was expected that from the 76 older adults, about 25 would report a fall in the follow-up period. All participants had normal or corrected to normal vision and none showed any significant signs of cognitive decline based on the Mini Mental State Evaluation. The protocol of the study was approved by the institutional Human Research Ethics Committee and all participants signed an informed consent form.

Protocol and materials. Participants were introduced to a gait initiation task. Participants stood on an AMTI AccuGait force platform (Advanced Mechanical Technology, Inc.) and were tasked with stepping off the force platform, walking down a pressure-sensitive walkway (GAITRite®, CIR Systems, Inc.) and stepping onto a curb. Whilst the current study investigated the gait initiation component of this experimental paradigm, the approach to the curb has been described elsewhere [18–20]. Throughout the experiment, the participants wore PLATO Visual Occlusion Spectacles

(Translucent Technologies Inc.). At the start of each trial, the spectacles occluded the participants vision for 15 seconds, during which time the stepping target was positioned in front of the participant (anti-slip material dimensions LxW: 0.30x1.50 m). The target was positioned in 10 different placements, ranging from 1 to 2.5 times the preferred step length of the participant (which was measured using the GAITRite walkway during three unconstrained walks performed a priori) from the edge of the force platform. As soon as the spectacles turned clear, participants were instructed to step onto the walkway, ensuring that they placed one footfall within their natural gait pattern onto the target. The participants continued along the walkway towards the curb and, upon reaching the other end, stepped up and onto the curb. In addition to the 10 placements of the target, one condition was added in which no target was presented. All conditions were repeated three times, leading to 33 trials in the experiment. The older participants completed a 12- month follow-up screening in which they returned a monthly report regarding any falls that occurred during gait-related activities that they performed as part of their everyday lives. The full protocol of this prospective follow-up has been reported elsewhere [19].

Independent Variables. All data analyses were completed using Matlab (R2018a, ©The Mathworks Inc.). Using the foot positions recorded with the GAITRite during the three trials without a target, an averaged, 'neutral', gait initiation pattern was computed. For the step onto the target in any walk, the distance between the positioning of this step and the neutral position was calculated as the amount of trial *adjustment required* (*AR*). This value represents locomotor pointing requirements, with larger *AR* representing more challenging locomotor pointing demands and hence more difficult gait-initiation.

Using the force platform, the CoP trajectory was recorded. The force platform sampled at 200 Hz and trajectories were smoothened using a second order, 5Hz low-pass Butterworth filter (similar to [21]). Typically, the CoP_x trajectory shifts towards the swing-leg side, representing a 'push off' to transfer all weight onto the standing leg. *Reaction Time (RT)* was detected as the moment after the spectacles turn clear at which the CoP_x velocity showed significant change towards the swing-leg side (a change resembling 10% of the difference between the current and maximum CoP_x velocity).

Dependent Variables. The main analysis was focussed on the CoP_x towards the standing leg. The start of this movement was defined by detecting when the CoP_x velocity first became larger than 10% of the maximum movement speed in that direction and the end was defined as when the CoP_x velocity first became smaller than this threshold [14,15]. The CoP motion-gap at any point in time (t) was equal to the CoP_x distance between the current CoP_x position and the end CoP_x position in the

CoP_x shift. Using the velocity profile of the closing of this gap, the time to closure (given the current velocity) or τ_{CoPx} was computed.

The function $\tau_G = 0.5\ (t - T_G^2 / t)$ was used to compute the tau-guide [8,10], where T_G is the total time taken to close the motion gap CoP_x and t represents the instant in time within the movement, which runs from 0 to T_G. Further, a recursive linear regression established the coupling between τ_G and τ_{CoPx}. To assess whether all of the CoP_x movement, or only the final part, was tau-guided, the R^2 of the regression was analysed. If the R^2 was smaller than 0.95, the data point furthest from the end-state was removed. This process was repeated until an R^2 of higher than 0.95 was reached. The percentage of the total movement that yielded a R^2 of higher than 0.95, that is, the *Percentage Coupled (PC),* was further analysed. The steepness index of the resulting τ_G - τ_{CoPx} regression was used to define the *coupling constant K*, following the linear relationship $\tau_{CoPx} = K * \tau_G$.

Statistical Analysis. In all statistical analyses, alpha was set to 0.05. In order to investigate reproducibility of the results of Spencer and Van der Meer [14], an independent samples t-test was used with the dependant variable *K* and age group (younger vs older adults) as factors. To gain further insight into the variability of *K* within participants and potential systematic differences between trials, Linear Mixed Effects (LME) modelling was used. Two predictive models were defined; the first one assessed the entire sample and the second assessed the relationship with falls incidence within the older sample. The significance of the coefficients related to the factors were interpreted as the effect of the factors. The first model can be summarized as:

$$K \sim 1 + AR*RT + (1 + AR*RT \mid AG)$$

in which '+' indicates the separation between the investigated effects and '*' indicates interactions between variables. *AR* represents the amount of *adjustment required* and *RT* represents *reaction time* for each gait initiation. The relationship between these variables and the τ_G -τ_{CoP} *coupling constant K* was allowed to have a different slope and interval for the younger and older adults (represented in the variable AG or *AgeGroup*). The second model used to analyse the influence of falls risk was used in the older cohort only and can be summarized as:

$$K \sim 1 + F*AR*RT + (1 + AR*RT \mid F)$$

in which *F* represents falls incidence and was a binary outcome (1 for fallers and 0 for non-fallers). Fallers were defined as the participants who reported at least one fall during their everyday gait in the 12-month follow-up period. Slopes and intercepts were allowed to vary for the effects of *AR* and *RT* between fallers and non-fallers in order to assess the effects of falls incidence.

Results

Results related to tau-coupling on a group level are summarized in Table 1. It was found that for both groups, on average, over 92% of the movements were tau-coupled, which indicated that tau-coupling reliably represented the movement. Unequal variances between age groups were detected using Levene's test and thus, an independent samples t-test adjusted for unequal variances for both groups was used. This test identified no differences in the used *K* value between age groups ($t(34.64) = -0.03$, $p = 0.98$).

Insert table 1 about here

Results from the LME modelling, investigating what factors influenced the *K* value of individual trials for all participants are summarized in Table 2. This table shows significant effects for the influence of RT on K (Coefficient Estimate, CE = -0.058, p = 0.004). This effect indicates that longer reaction times were associated with lower *K* values, as illustrated by the top panel in Figure 1. No other fixed or random effects were found to be significant contributors to predicting *K*.

Insert table 2 about here

In the prospective follow-up, 18 participants reported at least one fall during gait; these participants were classified as 'fallers' in the LME modelling. The LME modelling results related to falls incidence are summarized in Table 3. This table shows a significant effect for falls incidence (CE = 0.069, p = 0.003), which indicated that, in general, fallers showed higher values of *K*. Furthermore, a significant interaction was identified between falls incidence and RT (CE = -0.112, p = 0.036). This effect is illustrated in the bottom panel of Figure 1 and illustrates that, in fallers, higher reaction times were more strongly associated with lower *K* values, compared to non-fallers. The LME analysis did not identify any other fixed factors or random factors to significantly influence *K*.

Insert table 3 about here

Insert figure 1 about here

Discussion

This study investigated the CoP trajectories during gait initiation in a sample of younger and older adults. The aims of the study were to describe differences between fallers and non-fallers amongst older participants and to investigate the underlying dynamics in terms of tau-guidance. Results showed that the incidence of falls during gait in the 12 months following the assessment were associated with higher values of the coupling constant *K*. However, the average *K* for all groups remained in the safe control zone; below 0.5. *K* values between 0.5 and 1 indicate a strong deceleration at the end of the movement and potentially unstable movement patterns. Should the *K* values become larger than 0.5, as found in other studies with older adults [14], this could be problematic as this represents a later peak in the velocity profile and a hard closure of the movement gap, which may lead to an overshoot of the base of support.

Contrary to our expectation, we were unable to reproduce the previously reported relationship between coupling constant *K* and age [14]. Even though no relationship was found between the *K* values and the ages of different participant groups, it was interesting that the standard deviation of *K* values shown by the older group was much larger than for the younger group. A significant relationship was identified between movement preparation time and the coupling constant *K*, with longer preparation times associated with lower *K* values, particularly in fallers. Looking at Figure 1, it should be considered that the effect of reaction time could be mostly due to the higher variability in *K* with faster gait initiations. Together, these results indicate that it takes some time to optimally control the closure of CoP movement gaps, particularly in older adults. The higher variability in *K* found in the older groups might be due to this sample requiring longer to establish this functional relationship. However, since a consistently lower *K* (between 0 and 0.5) would be beneficial for safe movement control, it is important to consider movement preparation time as a factor of interest in the successful guidance of action.

The manipulation of difficulty in targeting did not show systematic influences on coupling constant *K.* It should be noted that the mere presence of the locomotor pointing task might have influenced the produced tau-coupling. In their study of unconstrained gait initiation, Spencer and Van der Meer [14] reported age-related increases in the coupling constant *K*. After introducing this targeting task, this effect was not present in the current study. The target stepping task could have demanded a more strongly controlled movement in comparison to unconstrained gait initiation. These results strengthen the view of motor control resulting from an interaction of constraints [22–24]. Specifically, it is not only the individual factors (e.g. age, falls risk) that influence prospective movement control, but rather the interaction of an individual with the environment and the task (locomotor pointing vs. unconstrained gait) that is relevant. The occlusion spectacles possibly further strengthened this effect, since they aided in focussing the participant on the locomotor pointing task when the lenses turned clear. These findings may be used to formulate strategies for safe movement control. However, more research is required to formulate further conclusions on this topic. Specifically, if introducing longer movement preparation times and visualizing stepping targets can assist in lowering the coupling constant *K,* this might be applied in falls prevention interventions.

In summary, the current study investigated tau-coupling in gait initiations and the variability in the coupling constant *K* summarizing the relationship between τ_G and τ_{CoP}. Results showed higher values of *K* are associated with prospectively reported falls during gait. Previously reported relations between *K* and age [14] were not reproduced present in the current study. Potentially, this is due to the inclusion of a locomotor pointing task in our protocol. This might have been more prescriptive than unconstrained gait initiations, thus helping the older participants in performing more controlled CoP movements. Future research is required to assess the practical implications of these findings, for instance in using stepping targets to help older adults optimize tau-guidance and minimize the risks for falls.

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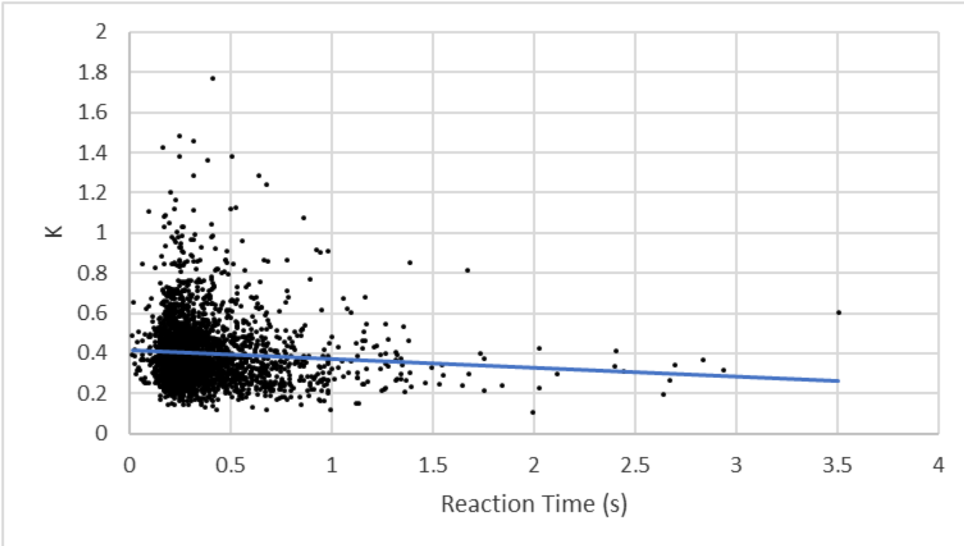

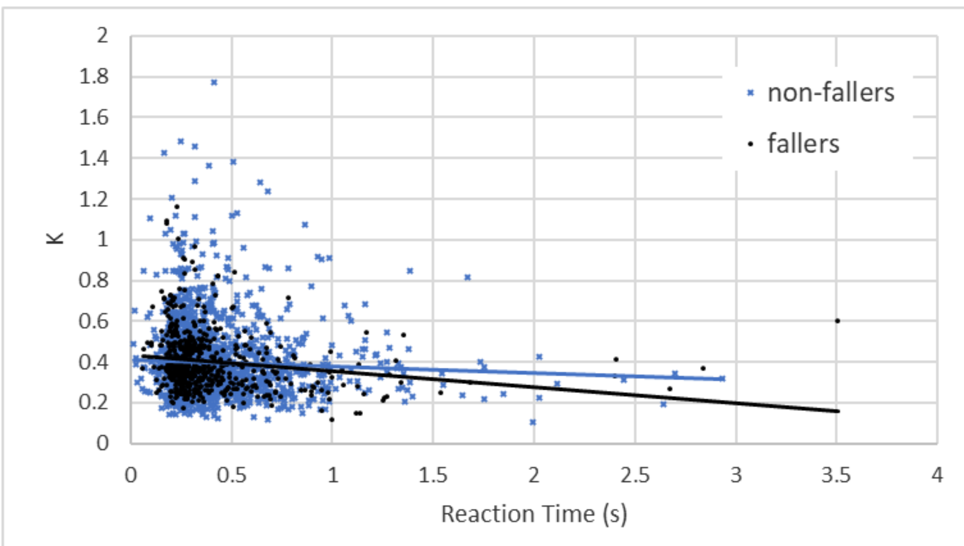

Figure 1. Scatter plot showing the relationship between the coupling constant (K) and Reaction Time for the 33 gait initiations performed by Top: all 92 participants; and Bottom: the older participants sub-divided into fallers (N=18) and non-fallers (N=58).

Table 1. Group-based means (± SD) for the Tau Coupling measures for the younger participants (N=16), older non-fallers (N=58), and older fallers (N=18).

	Younger Group	Older Non-fallers	Older fallers
Coupling constant *K*	0.40 ± 0.05	0.40 ± 0.09	0.41 ± 0.08
Percentage Coupling	95.26 ± 1.44	92.29 ± 5.26	93.05 ± 3.70

Table 2. Coefficients of the Linear Mixed Effects model predicting *K* for all participants

	Fixed Factors		
	Beta	SE	p value
Intercept	0.421	0.009	**< 0.001**
Adjustment Required	-0.000	< 0.001	0.414
Reaction Time	-0.058	0.02	**0.004**
Adjustment Required*Reaction Time	0.001	< 0.001	0.186

Note: The random factor 'Age Group' had no significant effect (p=0.530)

Significant effects (with alpha = 0.05) are presented bold-faced.

Table 3. Coefficients of the Linear Mixed Effects model predicting K in the sub-group of older adults

	Fixed Factors		
	Beta	SE	p value
Intercept	0.4	0.012	**< 0.001**
Falls	0.069	0.023	**0.003**
Adjustment Required	0.000	< 0.001	0.544
Reaction Time	-0.024	0.025	0.345
Falls*Adjustment Required	-0.000	< 0.001	0.45
Falls*Reaction Time	-0.112	0.052	**0.036**
Adjustment Required*Reaction Time	0.001	0.001	0.605
Falls*Adjustment Required*Reaction Time	-0.000	0.002	0.691

Note; effects of the random factor 'Falls' have been found non-significant (p=1.000)