The relation between limb segment coordination during walking and fall history in community-dwelling older adults

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Abstract

Control of the swing foot during walking is important to prevent falls. The trajectories of the swing foot are adjusted by coordination of the lower limbs, which is evaluated with uncontrolled manifold (UCM) analysis. A previous study that applied this analysis to walking revealed that older adults with fall history had compensatorily great segment coordination to stabilize the swing foot during normal walking. However, it is unknown whether the increase in segment coordination helps for preventing incident falls in the future. At baseline measurement, 30 older adults walked for 20 times at a comfortable speed. UCM analysis was performed to evaluate how the segment configuration in the lower limbs contributes to the swing foot stability. One year after the baseline visit, we asked the subjects if there were incident falls through a questionnaire. The univariate and multivariable logistic regression analyses were performed to assess the association between the index of segment coordination and incident falls with and without adjustment for gait velocity. Twenty-eight older adults who responded to the questionnaire were classified into older adults (n = 12) who had the incident fall and those (n = 16) who did not have falls. It was revealed that older adults who increased the segment coordination associated with swing foot stability tended to experience at least one fall within one year of measurement. The index of the UCM analysis can be a sensitive predictor of incident falls.

1. Introduction

Falls during walking is a serious problem in older adults (Berg et al., 1997; Stephen N Robinovitch et al., 2013). Given that the swing foot is an end effector during walking, sufficient swing foot control is important in preventing falls (Hamacher et al., 2016; Khandoker et al., 2008b, 2008a; Krishnan et al., 2013). In particular, during normal walking, the active control from the central nervous system (CNS) is necessary in the mediolateral (ML) direction, compared to that in the anterior posterior (AP) direction, which is controlled passively (Bauby and Kuo, 2000). On the basis of evidence that the sensitivity to perturbation during walking is higher in the ML direction and ML stability is crucial for walking (Bauby and Kuo, 2000; Maki, 1997; McAndrew et al., 2011, 2010; O'Connor and Kuo, 2009), evaluating swing foot control in the ML direction would be a feasible way to identify fall risk.

For walking, the movements of many elements in the body (e.g., bones and muscles) are necessary. Based on the discovery by Bernstein (1930) that high variability of elemental variables was related to the low variability of task-related variables across trials, the principle of motor abundance was suggested. CNS facilitates groups of solutions equally able to yield successful motor tasks rather than control elements (Gelfand and Latash, 1998). On the basis of a similar concept, the formulation of an uncontrolled manifold (UCM) hypothesis was developed (Scholz and Schöner, 1999). According to the hypothesis, CNS acts in a space of elemental variables and organizes in the subspace (UCM) corresponding to the stability of a task-related variable called performance variable in the present study. In the UCM analysis, two components of variance are quantified; one is V_{UCM}, which lies within the UCM space and does not affect the performance variable, and the other is V_{ORT}, which is orthogonal to the UCM space and affects the performance variable. An increase in V_{UCM} or decrease in V_{ORT} indicates that the performance variable is stable.

The UCM analysis has been applied to the motor tasks related to upper extremity, standing, and hopping performance (Freitas and Duarte, 2012; Hsu et al., 2014; Verrel et al., 2012; Yen and Chang, 2010). In previous studies centered on upper extremity tasks, older adults were found to have higher V_{ORT} and lower V_{UCM} than younger adults (Kapur et al., 2010; Verrel et al., 2012). In addition, a previous study has suggested that younger adults may utilize their motor abundance to control posture, allowing their joints to move freely in coordinated manner, whereas older adults could not confine to the strategy (Hsu et al., 2014). The postural control without falling is important during changing environments in daily life. UCM analysis is considered an appropriate method to accurately evaluate the segmental coordination related to an important variable for postural control.

There are several studies that have applied UCM analysis to walking (Eckardt and Rosenblatt, 2018; Krishnan et al., 2013; Papi et al., 2015; Yamagata et al., 2018), a number of which have investigated how the lower limbs contribute to swing foot stability during walking (Eckardt and Rosenblatt, 2018; Krishnan et al., 2013; Rosenblatt et al., 2015, 2014; Yamagata et al., 2018). During normal walking, in addition to the proportionately high V_{ORT} owing to aging, a high V_{UCM} has been recognized in healthy older adults without any fall experience (Krishnan et al., 2013). When adding fall history, an additional increase in V_{UCM} relative to than V_{ORT} was observed (Yamagata et al., 2018). As a high V_{UCM} during walking was observed in post-stroke patients as well as older adults, an excessive high V_{UCM} to stabilize swing foot during walking might not be simply helpful for preventing the incident falls (Krishnan et al., 2013; Yamagata et al., 2018). There is even possibility that high stability of swing foot by V_{UCM} observed in older adults with fall history lead to future falls because fall history is one of predictor of future falls (Shumway-cook and Gruber, 1997). There is currently no research that has explored the association between UCM indices and incident falls during walking, and investigating if UCM indices predict falls in the future using prospective cohort study is crucial.

The purpose of this study was to investigate that relationship between the indices of UCM analysis and incident falls in the future. We speculated that a greater increase in V_{UCM} than in V_{ORT} are related to incident falls.

2. Methods

2.1 Protocol

Thirty community-dwelling older adults (15 women) participated at a baseline visit in the present study. All individuals were over 60 years old and able to walk without assistance tools. The exclusion criteria consisted of neurological diseases and musculoskeletal conditions that may affect walking. Prior to the experiment, each subject was provided an explanation of the study and signed an informed consent form, which was approved by the Research Ethics Committee of Kyoto University. One year after the visit, we evaluated incident falls in the participants using a questionnaire. To investigate fall incidence, the participants were asked “Do you have any history of falling within the past year?” (Uemura et al., 2015; Wright et al., 2012). A fall was defined as an unexpected event during which the subjects came to rest on the ground, floor, or other lower level (Lamb et al., 2005).

At the baseline visit, the subjects walked on a 6-m pathway for 20 times at their own comfortable speed. A total of 40 steps, with the exclusion of the first four steps, were used for further analysis. We placed 22 spherical reflective markers on both sides of the body at the first metatarsal, fifth metatarsal, medial malleolus, lateral malleolus, medial femoral condyle, lateral femoral condyle, medial tibia condyle, lateral tibia condyle, greater trochanter, and anterior and posterior superior iliac spines. Using eight-infrared cameras at 100 Hz (Vicon MX; Vicon Motion Systems, Oxford), the kinematic data were recorded. The coordinate system was defined as x = anterior-posterior, y = medio-lateral, and z = vertical. Joint centers were identified using marker coordinate data (Tateuchi et al., 2017; Winter, 2009). The knee joint center was estimated as a point of intersection of the medial femoral condyle and lateral tibia condyle and lateral femoral condyle and medial tibia condyle. We defined the performance variable as a mediolateral trajectory of the swing foot, the median between the first and fifth metatarsals (FOOT). The elemental variables were defined as the lower segment angles (see next section).

For further analysis, data were time normalized (0–100%) from the right toe-off to the right initial contact, defined as the swing phase. Because of right leg dominance among all participants, focus was placed on the swing phase duration of the right leg. The calculated parameters were as follows: gait velocity, foot distance, segment angles, foot variabilities and segment angles, and UCM indices (see the next section). For the segment angles, the feet, shanks, thighs, and pelvis were included (as shown in Fig. 1). Foot distance was the average mediolateral distance between swing foot and stance foot, from which variability was calculated as the standard deviation across repeated trials. To evaluate fear of falls, we used 10-item questionnaire based on Fall Efficacy Scale (FES) (Tinetti et al., 1990); scores range from 1 ("not at all confident") to 4 ("completely confident"). Based on previous studies, the swing phase was equally divided into early-swing (0–33%), mid-swing (34–67%), and late-swing (68–100%) periods (Kao and Srivastava, 2018), and variables during each phase were averaged for further statistical comparisons.

2.2 UCM analysis

The UCM analysis was applied with a model that linked the segments in the lower limb. A detailed description of the UCM analysis and its application to the swing foot was reported in previous studies (Yamagata et al., 2018). Briefly, we identified seven segments (pelvis and bilateral feet, shanks, and thighs) from the markers and created a geometric model of 14 degrees of freedom (DOFs). Seven DOFs in the frontal plane (Θ_{Rfoot}, Θ_{Rshank}, Θ_{Rthigh}, Θ_{Pelvis}, Θ_{Lthigh}, Θ_{Lshank}, and Θ_{Lfoot}), six DOFs in the sagittal plane (α_{Rfoot}, α_{Rshank}, α_{Rthigh}, α_{Lthigh}, α_{Lshank}, and α_{Lfoot}), and one DOF in the transverse plane ($\alpha_{Pelvis,}$) were measured to calculate the accurate length of each segment (L) when projected onto the frontal plane (Fig. 1). We defined 14 DOFs as elemental variables and calculated the effect on the important performance variable (FOOT in this study). The elemental variables included the bilateral foot, shank, and thigh angles, in addition to the pelvic angle. The FOOT was defined as the right toe position relative to the left toe position.

FOOT and elemental variable matrix were expressed as:

$$FOOT = L_{Lfoot} \cos cos\, \alpha_{Lfoot} \ \sin sin\, \theta_{Lfoot} + \ L_{Lshank} \cos cos\, \alpha_{Lshank} \ \sin sin\, \theta_{Lshank} + \ L_{Lthigh} \cos$$

From this model, the relationship between FOOT trajectory and the elemental variable was estimated with the Jacobian (J). J is the matrix of the partial derivatives corresponding to changes in FOOT trajectory with respect to each segment angle. We used matrix decomposition to calculate the null space of the J. The null space, ε, is the (*n-d*) vector, the number of dimensions in the segmental configuration space ($n = 14$) and that of FOOT trajectories ($d = 1$) (Krishnan et al., 2013; Scholz and Schöner, 1999). At every percentage of swing, the differences in the segmental configurations from their mean $(\theta - \bar{\theta})$ were projected onto the null space:

$$\theta_{UCM} = \sum_{i=1}^{n-d} (\theta - \bar{\theta}) * \varepsilon_i$$

and onto a component orthogonal to this subspace:

$$\theta_{ORT} = (\theta - \bar{\theta}) - \theta_{UCM}$$

The variance (V_{UCM}) that does not affect the FOOT trajectories was calculated as the between-step average squared length of θ_{UCM}:

$$V_{UCM} = (n - d)^{-1} * N^{-1} * \sum (\theta_{UCM})^2$$

Similarly, the variance (V_{ORT}) that affects the FOOT trajectories was calculated as:

$$V_{ORT} = d^{-1} * N^{-1} * \sum (\theta_{ORT})^2$$

A synergy index (ΔV) was defined from V_{UCM} and V_{ORT}:

$$\Delta V = \frac{V_{UCM} - V_{ORT}}{V_{TOT}}$$

where

$$V_{TOT} = (\frac{1}{n})(dV_{ORT} + (n - d)V_{UCM})$$

For further analysis, ΔV was transformed using Fisher's z-transformation (ΔV_Z) that is commonly applied to normalize the index's distribution (Krishnan et al., 2013).

2.3 Statistical analysis

As primary outcomes, with incident falls as dependent variable (yes/ no), the univariate and multivariable logistic regression analyses were performed to assess the association between UCM index (V_{UCM} or V_{ORT}) in each swing phase (early-, mid- and late swing phase) and incident falls with and without adjustment for gait velocity. The relationship between incident falls and gait velocity, which is known as a fall predictor, was also tested with a univariate logistic regression analysis (Thebaldi et al., 2010). As gait velocity is thought to be related with UCM indices and incident falls, it was added as a covariate to the respective analyses with UCM indices to test the relationship between incident falls and adjusted UCM indices (Kao and Srivastava, 2018; Singh and Latash, 2011). All independent variables were screened for collinearity using bivariate Pearson's correlation coefficients.

As secondary outcomes, we tested the differences in general gait parameters evaluating gait strategy as well as physical characteristics between fallers and non-fallers. Independent t-tests were performed to compare ages, body masses, body heights, gait velocities, and FES scores. As fall history is viewed as a predictor of incident falls in the future, we also performed the chi-square test to analyze the relationship between fall history and future fall risk. Independent t-tests were used to compare foot distances, foot variability, segment angles, and segment variability between fallers and non-fallers (Mills and Barrett, 2001). Since there were violations for normality, log-transformation was used prior to t-tests for foot and segment variabilities. SPSS (PASW Statistics, Chicago) was used in all statistical tests, and the significance level was set at 0.05 for comparisons of physical characteristics. For the other variables, we used the method of Holm correction to adjust the p-values across the three swing phases (Chan et al., 2007). For the Holm correction, three p-values were ordered from smaller to larger and significance level was set at $p < 0.017$, $p < 0.025$, and $p < 0.05$ for the first, second, and third comparisons.

3. Results

Twenty-eight participants who answered a questionnaire after the baseline visit were included in the study. We divided the participants into two groups: older adults with no fall incidences (non-fallers; *n* = 16) and those who had at least one incident fall within a year after the baseline visit (fallers; *n* = 12). Eight of 12 fallers had a fall history prior to baseline assessment, and a significant relationship was observed between fall history and future fall risk ($\chi^2 = 4.86$, $p < 0.05$). There was no significant difference in age, body mass, body height, and FES score between groups, although gait velocity in fallers was significantly slower than that in non-fallers (Table 1). Regarding COM distance, there were significant effects of *Timing* (*F* [1, 26] = 14.5; p = 0.001) and *Group* (*F* [1, 26] = 6.1; $p < 0.05$). COM distance in fallers (22.9 ± 2.4 cm at toe-off and 19.7 ± 3.5 cm at heel strike) was significantly shorter than that in non-fallers (25.3 ± 3.3 cm at toe-off and 2.26 ± 4.1 cm at heel strike). COM distance at heel strike was significantly shorter than that at toe off.

In all planes, there were no significant group differences in average segment angles during walking (Table 2). Regarding the segment variability, the right shanks during mid-swing was significantly greater than those in non-fallers in the sagittal plane ($p < 0.01$; Table 3).

No significant differences in foot distance and variability between groups were found (Table 4), and gait velocity did not predict incident falls (OR = 0.002, 95% CI = 0.00–1.36, p = 0.06). Table 4 represents the average UCM indices across subjects during early-, mid-, late-swing. Regarding the relationship between UCM indices and incident falls, the odds ratio (OR) and 95% confidence interval are represented in Table 6. Note that, as the UCM indices were too small to calculate odds ratio (OR), V_{UCM} and V_{ORT} were multiplied by 10^4 and ΔV_Z was multiplied by 10^2 before the analysis. In the unadjusted models, V_{UCM} during mid-swing at baseline predicted incident falls (mid-swing OR = 1.39, 95% CI = 1.08–1.78, $p < 0.01$), with fallers demonstrating greater V_{UCM} than non-fallers. However, V_{ORT} and ΔV_Z between groups were similar and not predictive of incident falls. In the adjusted models by gait velocity, V_{UCM} during mid-swing at baseline was still a significant predictor (mid-swing OR = 1.35, 95% CI = 1.06–1.72, $p < 0.017$), although the other UCM indices did not predict incident falls.

4. Discussion

The purpose of this study was to investigate the relationship between the indices of UCM analysis and incident falls. An increase in V_{UCM} ($rad^2 \times 10^{-4}$) was related to incident falls, but V_{ORT} ($rad^2 \times 10^{-4}$) and ΔV_Z ($rad^2 \times 10^{-2}$) were not relevant. After adjusting the UCM indices by gait velocity, V_{UCM} ($rad^2 \times 10^{-4}$) during early-swing and mid-swing were found to be related to incident falls. These observations partially supported our hypotheses. This is the first study to reveal the relationship between UCM indices and incident falls, suggesting that V_{UCM} can be used as an index to predict incident falls.

A significant difference in fall history prior to baseline assessment was observed between the fallers and non-fallers, indicating that fall history is possibly related to future incident falls (Tromp et al., 2002). In addition to the fact, adjusted V_{UCM} during mid-swing phase was significantly related to incident falls. A previous study has shown that control of the central nervous system is active in the earlier phase before foot placement, when adjusting the foot contact position (Patla et al., 1999). When an accurate foot contact is required, healthy younger and older adults utilized high V_{UCM} from early- to mid-swing phase to compensate for an increase in V_{ORT} (Eckardt and Rosenblatt, 2018; Rosenblatt et al., 2014). In the present study, V_{UCM} during mid-swing could predict incident falls, unlike during early-swing. High control of the swing foot might be needed during mid-swing as compared with early-swing because the swing limb is closest to the stance limb during the phase.

Accurate foot placement during walking is important to create a proper base of support and keep walking stable, and the healthy subjects could explore motor flexibility even in challenging conditions since walking is habitual task in daily life. On the other hand, it was also shown that healthy older adults needed an increase in V_{UCM} to a greater extent than younger adults to compensate for high age-related motor noise (V_{ORT}) in such a complex task (Eckardt and Rosenblatt, 2018). The high motor flexibility by a greater increase in V_{UCM} relative to V_{ORT} was interpreted to contribute to reducing less optimal adaptive mechanics (e.g. joint stiffening) and reducing fall risks (Eckardt and Rosenblatt, 2018; Rosenblatt et al., 2014).

Surprisingly, however, the present study revealed that high V_{UCM} in older adults during normal walking was related to incident falls. In previous studies with normal walking task, the high kinematic synergy due to an increase in V_{UCM} to a greater extent than V_{ORT} was observed in post-stroke patients and older adults with high risk of falls, similar to our results (Kao and Srivastava, 2018; Yamagata et al., 2018). The results were interpreted as due to gait velocity or threat of falls on the kinematic synergy (Kao and Srivastava, 2018; Yamagata et al., 2018). Our results denied those interpretations; adjusted V_{UCM} by gait velocity was still associated with incident falls, and FES in fallers was similar to that in non-fallers. Older adults with high fall risks might require high V_{UCM} even during normal walking to compensate for any reasons, e.g. the degeneration of the sensory or motor system. Further study is needed to realize actual causes of change in the variance structure that leads to falls.

Fallers in this study possibly experienced incident falls because of paying attention to swing foot too much (Lai et al., 2012). In the previous studies and the present study, the swing foot in the ML direction was considered an important performance variable and was used to investigate the extent to which lower limb configurations contributed to performance variable stabilization (Eckardt and Rosenblatt, 2018; Krishnan et al., 2013; Rosenblatt et al., 2015; Yamagata et al., 2018). On the other hand, some previous studies have focused on the relationship between limb coordination and center of mass (COM) (Lee and Chou, 2006; Lugade et al., 2011). The COM in fallers might be unstable instead of the swing foot stability, caused by reduced balance control (Lugade et al., 2011); evaluating both controls of the swing foot and COM are important to represent walking stability.

V_{UCM} was associated with incident falls, but there was no association between V_{ORT} and incident falls. Several studies that investigated the effects of different subjects on UCM indices during walking revealed greater effects in V_{UCM} than in V_{ORT} (Eckardt and Rosenblatt, 2018; Kao and Srivastava, 2018; Krishnan et al., 2013; Yamagata et al., 2018). In most cases, the magnitude of V_{UCM} is bigger than that of V_{ORT}. Given that V_{UCM} have multiple functions, such as stabilizing the performance variables when the perturbations occur and performing secondary tasks successfully (Mattos et al., 2011; Zhang et al., 2010), V_{UCM} might be a sensitive index that reflects the changes in tasks or physical characteristics compared to V_{ORT}.

There was no significant difference in the foot distance and variability between fallers and non-fallers. Previous studies have shown that the trajectory and variability in the swing foot are useful indices to evaluate fall risks, unlike our results (Brach et al., 2005; Maki, 1997). The difference in the results might be affected by age and physical ability in older adults. Gait velocities in the fallers and non-fallers in the present study were found to be higher than those in older adults in previous studies (Brach et al., 2005; Maki, 1997). Fallers were observed to walk at a reduced velocity than non-fallers; however, older adults in this study were younger than those in the previous studies (Brach et al., 2005; Maki, 1997). To predict incident falls among older adults with relatively high physical function, like the subjects in this study, evaluations of segment coordination in addition to swing foot movement would be useful within further research.

There are some limitations in this study. First, we have not considered the effects of the trunk and upper limbs. Since walking is done with whole body segment motions, there might be effects on those segments. Second, we verified the exclusion criteria with self-report and interview. With specific assessments, some diseases in the exclusion criteria might be found in older adults in our study.

The other methodological considerations are accuracy and the details of falls. A previous study showed that the normal method of collecting cases of falls was a prospective reporting system (e.g. calendars or postcards) that requests immediate return of data or return at a certain period from 1 week to 3 months; the long delay between event and data recording would limit the verification of incident falls (Schwenk et al., 2012). Our method, a questionnaire survey conducted 1 year after the baseline visit, was not recommended and might have led to a recall bias in our results. In addition, we did not obtain details about the falls. Fallers might have included older adults who have fallen once or multiple times, which results in a difference in gait strategy, and the falls might not be due to poor control of the swing foot (Stephen N Robinovitch et al., 2013).

Despite the limitations, this is the first study to show the relationship between UCM indices and incident falls and reveal that V_{UCM} is an important predictor of incident falls. In the future, it is necessary to investigate what type of intervention will change the UCM indices and whether the changes actually reduce the fall risk.

5. Conclusions

It was revealed that older adults who experienced falls within a year maintained the stability of swing foot by increasing the variability of segment configurations during normal walking. V_{UCM} might be a sensitive index to predict falls in the future compared with V_{ORT}.

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Conflicts of interest

The authors have no conflicts of interest to disclose.

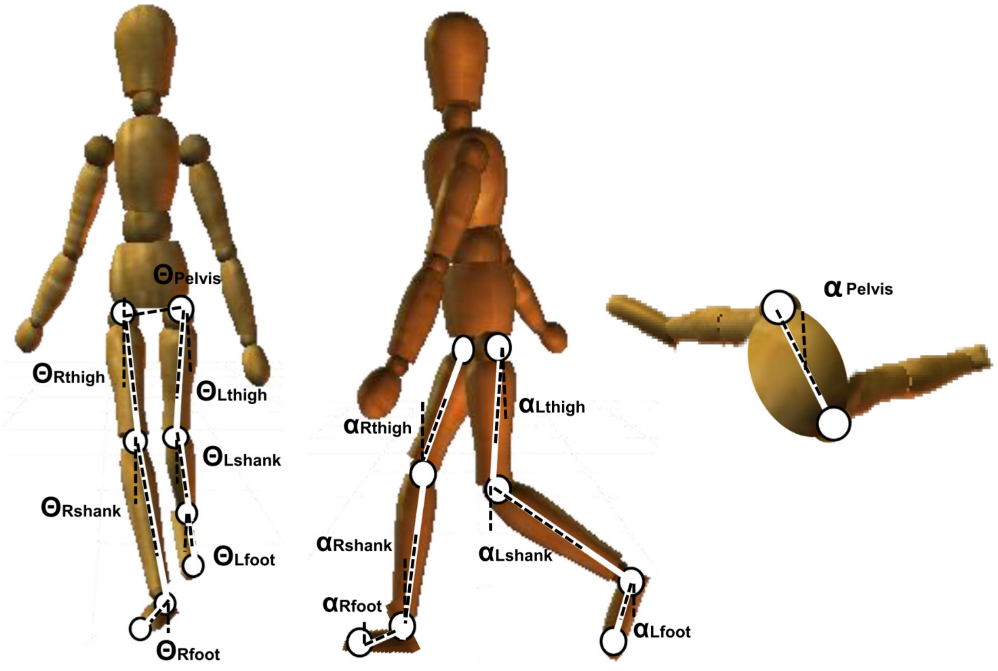

Figure 1. An illustration of the segment angles for the geometric model.

Seven segments and 14 degrees of freedoms were utilized for each elemental variable matrix: 7 degrees of freedom in the frontal plane (Θ) and 7 degrees of freedom in sagittal or transverse plane (α).

Rfoot right foot angle, *Rshank* right shank angle, *Rthigh* right thigh angle, *Pelvis* pelvis angle, *Lthigh* left thigh angle, *Lshank* left shank angle, *Lfoot* left foot angle

Table 1. Baseline characteristics

Variables	Fallers (n = 12)	Non-fallers (n = 16)
Age (years)	78.0 (4.7)	73.8 (7.9)
Height (cm)	154.1 (10.6)	160.2 (8.4)
Weight (kg)	52.2 (8.1)	58.4 (8.3)
FES score	33.3 (4.5)	34.9 (4.4)
Gait velocity (m/s)	1.1 (0.1)	1.3 (0.1)

Mean (SD)

Table 2. Averaged segment angle

Variables (rad)	Early-swing			Mid-swing			Late-swing		
	Fallers	Non-fallers	*p* value	Fallers	Non-fallers	*p* value	Fallers	Non-fallers	*p* value
Θ_{Rfoot}	-1.47 (0.13)	-1.43 (0.10)	0.36	-1.19 (0.16)	-1.15 (0.10)	0.46	-0.52 (0.23)	-0.45 (0.28)	0.53
Θ_{Rshank}	0.12 (0.09)	0.15 (0.06)	0.22	0.05 (0.04)	0.08 (0.05)	0.24	0.04 (0.04)	0.05 (0.03)	0.97
Θ_{Rthigh}	0.02 (0.03)	0.001 (0.04)	0.28	0.02 (0.05)	0.006 (0.04)	0.38	0.05 (0.04)	0.04 (0.03)	0.38
Θ_{Pelvis}	1.60 (0.04)	1.62 (0.03)	0.19	1.59 (0.02)	1.60 (0.02)	0.31	1.59 (0.01)	1.60 (0.01)	0.35
Θ_{Lthigh}	-0.08 (0.03)	-0.08 (0.02)	0.96	-0.08 (0.02)	-0.08 (0.03)	0.99	-0.07 (0.04)	-0.07 (0.03)	0.60
Θ_{Lshank}	-0.12 (0.04)	-0.11 (0.04)	0.56	-0.13 (0.03)	-0.12 (0.04)	0.51	-0.13 (0.04)	-0.12 (0.04)	0.66
Θ_{Lfoot}	0.37 (0.29)	0.50 (0.19)	0.16	0.37 (0.27)	0.49 (0.19)	0.18	0.29 (0.24)	0.38 (0.18)	0.28
α_{Rfoot}	-1.42 (0.16)	-0.07 (0.11)	0.06	-0.81 (0.14)	-0.90 (0.12)	0.10	-0.14 (0.06)	-0.16 (0.08)	0.62
α_{Rshank}	0.91 (0.06)	0.92 (0.06)	0.67	0.53 (0.09)	0.55 (0.08)	0.58	-0.19 (0.09)	-0.20 (0.05)	0.72
α_{Rthigh}	0.04 (0.05)	0.06 (0.05)	0.40	-0.29 (0.04)	-0.29 (0.04)	0.39	-0.37 (0.03)	-0.39 (0.05)	0.25
α_{Pelvis}	1.65 (0.06)	1.65 (0.06)	0.89	1.57 (0.05)	1.56 (0.04)	0.60	1.51 (0.06)	1.48 (0.05)	0.13
α_{Lthigh}	-0.22 (0.06)	-0.25 (0.07)	0.28	0.02 (0.04)	0.02 (0.05)	0.87	0.21 (0.06)	0.22 (0.06)	0.61
α_{Lshank}	0.07 (0.06)	0.06 (0.05)	0.81	0.18 (0.05)	0.18 (0.06)	0.78	0.35 (0.06)	0.37 (0.05)	0.34
α_{Lfoot}	-1.26 (0.04)	-1.23 (0.05)	0.10	-1.23 (0.06)	-1.19 (0.05)	0.12	-1.10 (0.08)	-1.04 (0.09)	0.13

Average segment angles within each swing phase in the frontal plane (Θ_{Rfoot}, Θ_{Rshank}, Θ_{Rthigh}, Θ_{Pelvis}, Θ_{Lthigh}, Θ_{Lshank}, and Θ_{Lfoot}), the sagittal plane (α_{Rfoot}, α_{Rshank}, α_{Rthigh}, α_{Lthigh}, α_{Lshank}, and α_{Lfoot}), and the transverse plane (α_{Pelvis}). Mean (SD).

Rfoot right foot angle, *Rshank* right shank angle, *Rthigh* right thigh angle, *Pelvis* pelvis angle, *Lthigh* left thigh angle, *Lshank* left shank angle, *Lfoot* left foot angle

Table 3. Variability of segment angle (10^{-3})

Variables (rad)	Early-swing			Mid-swing			Late-swing		
	Fallers	Non-fallers	*p* value	Fallers	Non-fallers	*p* value	Fallers	Non-fallers	*p* value
Θ_{Rfoot}	5.65 (1.57)	5.20 (1.19)	0.43	6.29 (2.27)	4.86 (1.28)	0.07	19.4 (9.85)	13.89 (5.88)	0.08
Θ_{Rshank}	4.08 (0.89)	4.15 (1.59)	0.90	2.96 (0.70)	2.65 (0.89)	0.25	1.74 (0.46)	1.87 (1.04)	0.98
Θ_{Rthigh}	1.31 (0.31)	1.44 (0.35)	0.31	1.49 (0.39)	1.41 (0.32)	0.57	1.44 (0.36)	1.62 (0.74)	0.51
Θ_{Pelvis}	1.13 (0.22)	1.24 (0.65)	0.86	1.05 (0.23)	0.99 (0.32)	0.41	0.99 (0.26)	0.97 (0.30)	0.72
Θ_{Lthigh}	1.46 (0.26)	1.52 (0.44)	0.85	1.25 (0.23)	1.27 (0.38)	0.93	1.44 (0.37)	1.43 (0.42)	0.94
Θ_{Lshank}	1.73 (0.50)	1.46 (0.40)	0.14	1.60 (0.43)	1.48 (0.36)	0.44	1.82 (0.39)	1.77 (0.45)	0.68
Θ_{Lfoot}	9.81 (3.27)	8.27 (3.79)	0.20	10.24 (3.39)	8.06 (3.21)	0.10	8.92 (2.59)	7.63 (2.44)	0.84
α_{Rfoot}	5.43 (0.94)	4.96 (0.75)	0.15	7.56 (1.90)	6.55 (1.29)	0.20	5.20 (1.56)	4.48 (1.05)	0.43
α_{Rshank}	2.90 (0.85)	2.30 (0.29)	0.03	6.41 (1.15)	5.21 (0.92)	0.004 *	5.75 (1.89)	4.69 (0.85)	0.10
α_{Rthigh}	3.58 (0.67)	3.18 (0.97)	0.16	2.69 (0.74)	2.42 (0.62)	0.34	1.96 (0.58)	1.86 (0.63)	0.62
α_{Pelvis}	3.44 (1.22)	3.52 (1.70)	0.99	3.19 (0.98)	3.04 (0.77)	0.78	3.26 (0.84)	3.09 (0.85)	0.57
α_{Lthigh}	2.43 (0.67)	2.56 (0.63)	0.58	1.92 (0.41)	2.11 (0.45)	0.25	2.27 (0.59)	2.05 (0.62)	0.30
α_{Lshank}	2.65 (0.52)	2.34 (0.71)	0.15	2.47 (0.51)	2.05 (0.47)	0.04	2.75 (0.33)	2.48 (0.36)	0.05
α_{Lfoot}	1.05 (0.91)	0.69 (0.36)	0.15	1.95 (1.07)	1.49 (1.05)	0.16	4.36 (1.50)	4.25 (1.63)	0.80

The variabilities of segment angle in the frontal plane (Θ) and sagittal (or transverse) plane (α) are shown.

Mean (SD), * Significantly greater in fallers than non-fallers.

Rfoot right foot angle, *Rshank* right shank angle, *Rthigh* right thigh angle, *Pelvis* pelvis angle, *Lthigh* left thigh angle, *Lshank* left shank angle, *Lfoot* left foot angle

Table 4. Averaged foot distance and foot variability

Variables (cm)	Early-swing			Mid-swing			Late-swing		
	Fallers	Non-fallers	*p* value	Fallers	Non-fallers	*p* value	Fallers	Non-fallers	*p* value
Foot distance	13.10 (3.93)	14.49 (2.67)	0.29	15.14 (3.86)	16.61 (2.55)	0.21	13.85 (4.77)	15.57 (2.98)	0.23
Foot variability	1.87 (0.41)	2.28 (0.83)	0.13	1.09 (0.42)	1.17 (0.39)	0.19	1.85 (0.49)	1.97 (0.76)	0.34

The swing foot distance and swing foot variability during early-, mid-, late-swing. Mean (SD).

Table 5. Average UCM indices across subjects

Variables (rad^2)	Fallers			Non-fallers		
	Early-swing	Mid-swing	Late-swing	Early-swing	Mid-swing	Late-swing
V_{UCM} (10^{-4})	21.39 (7.00)	26.68 (8.13)	49.18 (30.89)	12.99 (3.46)	45.10 (4.37)	26.01 (10.36)
V_{ORT} (10^{-4})	9.80 (4.23)	3.04 (2.33)	7.06 (3.65)	9.18 (8.85)	2.33 (1.69)	7.68 (7.11)
ΔV_Z (10^{-2})	74.70 (69.03)	105.62 (99.93)	96.21 (18.48)	69.03 (12.62)	99.94 (13.71)	86.54 (14.52)

UCM indices during early-, mid-, late-swing. Mean (SD).

References

Bauby, C.E., Kuo, A.D., 2000. Active control of lateral balance in human walking. J. Biomech. 33, 1433–1440. doi:10.1016/S0021-9290(00)00101-9

Berg, W.P., Alessio, H.M., Mills, E.M., Tong, C., 1997. Circumstances and consequences of falls in independent community-dwelling older adults. Age Ageing 26, 261–8. doi:10.1093/ageing/26.4.261

Brach, J.S., Berlin, J.E., VanSwearingen, J.M., Newman, A.B., Studenski, S.A., 2005. Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed. J. Neuroeng. Rehabil. 2, 21. doi:10.1186/1743-0003-2-21

Chan, A.O.O., Jim, M.H., Lam, K.F., Morris, J.S., Siu, D.C.W., Tong, T., Ng, F.H., Wong, S.Y., Hui, W.M., Chan, C.K., Lai, K.C., Cheung, T.K., Chan, P., Wong, G., Yuen, M.F., Lau, Y.K., Lee, S., Szeto, M.L., Wong, B.C.Y., Lam, S.K., 2007. Prevalence of colorectal neoplasm among patients with newly diagnosed coronary artery disease. JAMA 298, 1412–1419. doi:10.1001/jama.298.12.1412

Eckardt, N., Rosenblatt, N.J., 2018. Healthy aging does not impair lower extremity motor flexibility while walking across an uneven surface. Hum. Mov. Sci. 62, 67–80. doi:10.1016/j.humov.2018.09.008

Freitas, S.M.S.F., Duarte, M., 2012. Joint coordination in young and older adults during quiet stance: Effect of visual feedback of the center of pressure. Gait Posture 35, 83–87. doi:10.1016/j.gaitpost.2011.08.011

Gelfand, I.M., Latash, M.L., 1998. On the Problem of Adequate Language in Motor Control. Motor Control 2, 306–313. doi:10.1123/mcj.2.4.306

Hamacher, D., Hamacher, D., Herold, F., Schega, L., 2016. Effect of dual tasks on gait variability in walking to auditory cues in older and young individuals. Exp. Brain Res. 234, 3555–3563. doi:10.1007/s00221-016-4754-x

Hsu, W.L., Lin, K.H., Yang, R. Sen, Cheng, C.H., 2014. Use of motor abundance in old adults in the regulation of a narrow-based stance. Eur. J. Appl. Physiol. 114, 261–271. doi:10.1007/s00421-013-2768-7

Kao, P.-C., Srivastava, S., 2018. Mediolateral footpath stabilization during walking in people following stroke. PLoS One 13, 1–17. doi:https://doi.org/10.1371/journal.pone.0208120

Kapur, S., Zatsiorsky, V.M., Latash, M.L., 2010. Age-related changes in the control of finger force vectors. J Appl Physiol 109, 1827–1841. doi:10.1152/japplphysiol.00430.2010.

Khandoker, A.H., Palaniswami, M., Begg, R.K., 2008a. A comparative study on approximate entropy measure and poincaré plot indexes of minimum foot clearance variability in the elderly during walking. J. Neuroeng. Rehabil. 5, 4. doi:10.1186/1743-0003-5-4

Khandoker, A.H., Taylor, S.B., Karmakar, C.K., Begg, R.K., Member, S., Palaniswami, M., Member, S., 2008b. Investigating Scale Invariant Dynamics in Minimum Toe Clearance Variability of the Young and Elderly During Treadmill Walking. IEEE Trans Neural Syst Rehabil Eng 16, 380–389.

Krishnan, V., Rosenblatt, N.J., Latash, M.L., Grabiner, M.D., 2013. The effects of age on stabilization of the mediolateral trajectory of the swing foot. Gait Posture 38, 923–928. doi:10.1016/j.gaitpost.2013.04.023

Lai, D.T.H., Taylor, S.B., Begg, R.K., 2012. Prediction of foot clearance parameters as a precursor to forecasting the risk of tripping and falling. Hum. Mov. Sci. 31, 271–283. doi:10.1016/j.humov.2010.07.009

Lamb, S.E., Jørstad-Stein, E.C., Hauer, K., Becker, C., 2005. Development of a common outcome data set for fall injury prevention trials: The Prevention of Falls Network Europe consensus. J. Am. Geriatr. Soc. 53, 1618–1622. doi:10.1111/j.1532-5415.2005.53455.x

Lee, H.J., Chou, L.S., 2006. Detection of gait instability using the center of mass and center of pressure inclination angles. Arch. Phys. Med. Rehabil. 87, 569–575. doi:10.1016/j.apmr.2005.11.033

Lugade, V., Lin, V., Chou, L.S., 2011. Center of mass and base of support interaction during gait. Gait Posture 33, 406–411. doi:10.1016/j.gaitpost.2010.12.013

Maki, B.E., 1997. Gait changes in older adults: Predictors of falls or indicators of fear? J. Am. Geriatr. Soc. 45, 313–320. doi:10.1111/j.1532-5415.1997.tb00946.x

Mattos, D.J.S., Latash, M.L., Park, E., Kuhl, J., Scholz, J.P., 2011. Unpredictable elbow joint perturbation during reaching results in multijoint motor equivalence. J. Neurophysiol. 106, 1424–1436. doi:10.1152/jn.00163.2011

McAndrew, P.M., Dingwell, J.B., Wilken, J.M., 2010. Walking variability during continuous pseudo-random oscillations of the support surface and visual field. J. Biomech. 43, 1470–1475. doi:10.1016/j.jbiomech.2010.02.003

McAndrew, P.M., Wilken, J.M., Dingwell, J.B., 2011. Dynamic stability of human walking in visually and mechanically destabilizing environments. J. Biomech. 44, 644–649. doi:10.1016/j.jbiomech.2010.11.007

Mills, P.M., Barrett, R.S., 2001. Swing phase mechanics of healthy young and elderly men. Hum. Mov. Sci. 20, 427–446. doi:10.1016/S0167-9457(01)00061-6

O'Connor, S.M., Kuo, A.D., 2009. Direction-Dependent Control of Balance During Walking and Standing. J. Neurophysiol. 102, 1411–1419. doi:10.1152/jn.00131.2009

Papi, E., Rowe, P.J., Pomeroy, V.M., 2015. Analysis of gait within the uncontrolled manifold hypothesis: Stabilisation of the centre of mass during gait. J. Biomech. 48, 324–331. doi:10.1016/j.jbiomech.2014.11.024

Patla, A.E., Prentice, S.D., Rietdyk, S., Allard, F., Martin, C., 1999. What guides the selection of alternate foot placement during locomotion in humans. Exp. Brain Res. 128, 441–450. doi:10.1007/s002210050867

Rosenblatt, N.J., Hurt, C.P., Latash, M.L., Grabiner, M.D., 2014. An apparent contradiction: Increasing variability to achieve greater precision? Exp. Brain Res. 232, 403–413. doi:10.1007/s00221-013-3748-1

Rosenblatt, N.J., Latash, M.L., Hurt, C.P., Grabiner, M.D., 2015. Challenging gait leads to stronger lower-limb kinematic synergies: The effects of walking within a more narrow pathway. Neurosci. Lett. 600, 110–114. doi:10.1016/j.neulet.2015.05.039

Scholz, J.P., Schöner, G., 1999. The uncontrolled manifold concept: Identifying control variables for a functional task. Exp. Brain Res. 126, 289–306. doi:10.1007/s002210050738

Schwenk, M., Lauenroth, A., Stock, C., Moreno, R.R., Oster, P., McHugh, G., Todd, C., Hauer, K., 2012. Definitions and methods of measuring and reporting on injurious falls in randomised controlled fall prevention trials: A systematic review. BMC

Med. Res. Methodol. 12, 50. doi:10.1186/1471-2288-12-50

Shumway-cook, A., Gruber, W., 1997. Predicting the Probability for Falls in Community-Dwelling Older Adults 77, 812–819.

Singh, T., Latash, M.L., 2011. Effects of muscle fatigue on multi-muscle synergies. Exp. Brain Res. 214, 335–350. doi:10.1007/s00221-011-2831-8

Stephen N Robinovitch, Fabio Feldman, Yijian Yang, Rebecca Schonnop, Pet Ming Lueng, Thiago Sarraf, Joanie Sims-Gould, Marie Loughin, 2013. Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study. Lancet 381, 47–54. doi:10.1016/S0140-6736(12)61263-X.Video

Tateuchi, H., Koyama, Y., Akiyama, H., Goto, K., So, K., Kuroda, Y., Ichihashi, N., 2017. Daily cumulative hip moment is associated with radiographic progression of secondary hip osteoarthritis. Osteoarthr. Cartil. 25, 1291–1298. doi:10.1016/j.joca.2017.02.796

Thebaldi, M.S., Da Rocha, M.S., Sandri, D., Felisberto, A.B., Avelino Neto, S., 2010. Independent Influence of Gait Speed and Step Length on Stability and Fall Risk. Gait Posture 32, 378–382. doi:10.1016/j.gaitpost.2010.06.013.Independent

Tinetti, M.E., Richman, D., Powell, L., 1990. Falls efficacy as a measure of fear of falling. Journals Gerontol. 45, 239–243. doi:10.1093/geronj/45.6.P239

Tromp, A.., Pluijm, S.M.., Smit, J.., Deeg, D.J.., Bouter, L.., Lips, P., 2002. Fall-risk screening test: A prospective study on predictors for falls in community-dwelling elderly. J. Clin. Epidemiol. 54, 837–844. doi:10.1016/s0895-4356(01)00349-3

Uemura, K., Shimada, H., Makizako, H., Doi, T., Tsutsumimoto, K., Lee, S., Umegaki, H., Kuzuya, M., Suzuki, T., 2015. Effects of Mild Cognitive Impairment on the Development of Fear of Falling in Older Adults: A Prospective Cohort Study. J. Am. Med. Dir. Assoc. 16, 1104.e9-1104.e13. doi:10.1016/j.jamda.2015.09.014

Verrel, J., Lövdén, M., Lindenberger, U., 2012. Normal aging reduces motor synergies in manual pointing. Neurobiol. Aging 33, 201–210. doi:10.1016/j.neurobiolaging.2010.07.006

Vittinghoff, E., McCulloch, C.E., 2007. Relaxing the rule of ten events per variable in logistic and cox regression. Am. J. Epidemiol. 165, 710–718. doi:10.1093/aje/kwk052

Winter, D.A., 2009. Biomechanics and Motor Control of Human Movement, 4th ed. Hoboken, John Wiley & Sons.

Wright, R.L., Peters, D.M., Robinson, P.D., Sitch, A.J., Watt, T.N., Hollands, M.A., 2012. Differences in axial segment reorientation during standing turns predict multiple falls in older adults. Gait Posture 36, 541–545. doi:10.1016/j.gaitpost.2012.05.013

Yamagata, M., Tateuchi, H., Shimizu, I., Ichihashi, N., 2018. The effects of fall history on kinematic synergy during walking. J. Biomech. 82, 204–210. doi:10.1016/j.jbiomech.2018.10.032

Yen, J.T., Chang, Y.-H., 2010. Rate-dependent control strategies stabilize limb forces during human locomotion. J. R. Soc. Interface 7, 801–810. doi:10.1098/rsif.2009.0296

Zhang, W., Scholz, J.P., Zatsiorsky, V.M., Latash, M.L., 2010. What Do Synergies Do? Effects of Secondary Constraints on Multidigit Synergies in Accurate

Force-Production Tasks. J. Neurophysiol. 99, 500–513. doi:10.1152/jn.01029.2007