Relation between frontal plane center of mass position stability and foot elevation during obstacle crossing

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Abstract

High foot elevation during obstacle crossing is viewed as a conservative strategy in older adults, but excessive foot elevation may result in large mediolateral center of mass (CoM) displacement. Since an incorrect transfer of CoM can lead to balance loss during locomotion, both appropriate foot elevation and CoM position must be controlled and coordinated by adjusting body segment positions. However, no studies have revealed time profiles of CoM position by coordinated segment movements and the relation of foot elevation with CoM position during obstacle crossing. Twenty-five healthy older adults crossed an obstacle (depth: 1 cm, width: 60 cm, height: 8cm) during comfortable-speed walking. Synergy indices were calculated during lead- and trail-limb swing using uncontrolled manifold analysis. High synergy index values indicate a strong multi-joint kinematic synergy, or co-fluctuations in segment movements, to control CoM position. The maximum foot heights of the swing limbs were calculated as the maximum vertical distance between the most distal foot point and the ground. In the mediolateral direction, synergy index values during early lead-limb swing were significantly greater than during early- trail-limb swing, and in the vertical direction, large synergy index values were found during early- and mid-swing phases. Moreover, maximum trail-foot height was correlated to vertical synergy index during early phase. CoM position was not well controlled by a kinematic synergy during trail-limb swing and the low control of CoM position was observed with great trail-foot height. The results suggest that a conservative strategy with great trail-foot height would not always be helpful for successful obstacle crossing.

1. Introduction

Obstacle crossing requires both proper foot elevation and body balance. Regarding foot elevation, conflicting results have been found; lower foot elevation in older adults compared to younger adults(Mcfadyen and Prince, 2002), and greater foot elevation by age and fall risk (Lu et al., 2006; Muir et al., 2019; Pan et al., 2016). It is viewed that low foot elevation leads to a high risk of tripping and high foot elevation is a conservative strategy to prevent tripping. The latter studies, however, also found high step width variability, which may reflect poor control of center of mass (CoM) in the frontal plane (Muir et al., 2019; Pan et al., 2016). While insufficient foot clearance clearly leads to a high risk of tripping, there is a possibility that excessive foot elevation would affect CoM position and lead to balance loss instead (Galna et al., 2013).

There are some studies focused on CoM trajectories during obstacle crossing (Chou et al., 2003; Hahn and Chou, 2003; Lee and Chou, 2006). Older adults with complaints of imbalance had greater mediolateral CoM displacement and greater inclination angle between CoM and center of pressure in the frontal plane during obstacle crossing, compared to healthy adults (Chou et al., 2003; Hahn and Chou, 2003; Lee and Chou, 2006). Despite the significant difference in frontal CoM displacement, no individual segment movement effect was found by balance ability (Hahn and Chou, 2003), that would relate to the fact that CoM position is directly dependent on segment configuration. Given that posture balance would easily become unstable in the frontal plane compared to the sagittal plane during walking (Bauby and Kuo, 2000; Maki and McIlroy, 2006; Nevitt and

Cummings, 1993), both well-controlled frontal CoM position and proper foot elevation are crucial for successful obstacle crossing.

Previous studies have shown that the first limb (lead limb) and second limb (trail limb) when stepping over an obstacle are independently controlled (Heijnen et al., 2014, 2012). During lead-limb crossing, the real-time visual information of distance to the obstacle is used to update and calibrate the movement, whereas during trail-limb crossing, such information is unavailable, and this reduced information can lead to inappropriate movement and high risk of falls (Heijnen et al., 2014). CoM position in older adults remains posterior relative to younger adults when crossing an obstacle (Hak et al., 2019), leading to larger distance between CoM position and base of support (BoS) during early trail-limb swing phase compared to other phases. Taken together, CoM position during lead-limb swing appears to be controlled relatively well, but may be easily disturbed during trail-limb swing.

Synergistic control of an abundant set of elements such as joints is needed to succeed any activities, including obstacle crossing (Gelfand and Latash, 1998; Latash, 2012). “Synergy” is defined as a neural organization that ensure co-variation (coordination) of the elements for different performance variables in a task-specific manner; a performance variable is a quantitative representation of the task goal (See Appendix1). One way to quantify the strength of synergies is to use a technique called uncontrolled manifold (UCM) analysis. UCM is a technique that assumes that elements (i.e., body segments in this study) are coordinated to control the performance variable(s) (i.e., CoM position in this study) (Scholz and Schöner, 1999). In this study, like in other gait studies involving UCM analysis, we presume that the mean CoM trajectory is the performance variable (Black et al., 2007), and that individuals attempt to replicate this trajectory. This may or may not be representative of the actual task goal – from the individual's perspective – but since the CoM position and trajectory are relevant to balance control, this study adopts the CoM trajectory as a starting point for considering understanding how many degrees of freedom relate to its potential control.

To calculate the synergy index, across-trials variance of segmental configuration was partitioned into two components: variance that affects salient performance variable (orthogonal variance: V_{ORT}), and variance that does not affect the performance variable (UCM variance: V_{UCM}). High synergy index values, due to an increase in V_{UCM} or a decrease in V_{ORT}, reflect a strong synergy. This, by itself, is indicative of functionality: strong synergies generally imply that redundant elements are working together in a coordinated manner to achieve some common, functional goal (Latash, 2012). A variety of research has shown that synergies are functionally important for controlling performance, for example: retaining balance and forward progress when encountering different environments and unexpected perturbations (Hsu et al., 2013; Mattos et al., 2011). Additionally, some previous studies have seen lower synergy index in older adults and patients with motor impairments compared to healthy adults, indicating functional decline (Falaki et al., 2016; Hsu et al., 2013).

Until now, segmental variables, such as segment angles, trajectories of CoM position, and foot elevation, have been independently evaluated during obstacle crossing, but there has been no study that assesses the relations of segmental variables with CoM control. UCM analysis is a feasible way to verify the extent to which CoM position is controlled by coordinated segment movements, synergy. Also, the relation between foot elevation and synergy index for trajectories of CoM position is still unclear. The first purpose of this study was to describe the temporal changes in kinematic synergies during obstacle crossing, and to show the timing with lower synergy index by comparing in two ways; comparisons in the synergy indices between lead- and trail-limb crossing within each swing phase, and comparisons in the synergy indices among early, mid, and late swing phases during lead- and trail-limb crossing. The second purpose was to quantify the relation between obstacle-foot clearance height and synergy strength. This was an exploratory study, implying that we made specific a priori predictions regarding neither temporal changes in synergy strength, nor the relation between synergy strength and foot clearance height. We instead tested the null hypotheses of: equivalent synergistic behavior in leading and trailing limbs, and no correlations between UCM indices and max foot clearance height.

2. Methods

Participants

Twenty-five older adults participated in this study. Inclusion criteria were community-dwelling older adults over 60 years old who could walk without assistance and who had no diseases, neurological disorders or musculoskeletal injuries, that would affect walking performance. Prior to the experiments, all participants were fully informed about the purpose and procedures of this study and provided informed consent. Ethical approval was granted by the Research Ethics Committee of Kyoto University (R0433-3).

Procedure

The participants walked 20 times at their comfortable speed along a 6-m walkway which contained an obstacle (depth: 1 cm, width: 60 cm, height: 8cm) 3 m from the start. The 8-cm obstacle height was chosen as a maximum height that is likely found in homes (Said et al., 2001). Participants were asked to cross the obstacle with their dominant leg (defined as the kicking foot). All participants were right-side dominant. Since limb dominance was not of empirical interest, the “dominant” and “non-dominant” limbs are referred to as “Lead” and “Trail” limbs, respectively, in the remainder of this manuscript. There were approximately five minutes of practice to become accustomed to the task.

The kinematic data during obstacle crossing were collected at 100 Hz using an eight-camera Vicon Motion System (VICON MX, Oxford). The reflective markers were placed on both sides of body and trunk as follows: forehead, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, medial and lateral femoral condyles, medial tibia condyle, head of fibula, medial condyle of tibia, medial and lateral malleolus, 7th cervical vertebra, and 10th thoracic vertebra. We also placed markers on both sides of the calcaneus and second metatarsal. We focused on swing phase that would include large changes of the UCM indices during lead- and trail-limb crossing. CoM were difined as the CoM position of the whole body calculated from the sum of each segmental CoM (Tokuda et al., 2017; Winter, 2009; Yamagata et al., 2018). The swing phases (from toe-off until initial contact) during lead- and trail-limb crossing were extracted and time normalized (100%) for each phase separately.

Parameters

CoM displacements were calculated in the mediolateral and vertical directions. Mediolateral CoM displacements were expressed relative to the ankle joint of the stance limb, and vertical CoM displacements were expressed relative to the ground. We also evaluated the maximum foot height (mFH) and step lengths of the lead and trail limbs. mFH was defined as the maximum vertical distance between a marker placed on second metatarsal and ground during each limb crossing (Lead_mFH, Trail_mFH), and stride lengths were calculated for each limb crossing an obstacle (Lead_length, Trail_length). The averages and variabilities (standard deviations) of the above variables were calculated across 20 steps for further statistical comparisons.

UCM analysis

A detailed description of UCM analysis is given in a study by Scholz et al., and trajectories of CoM position in the mediolateral (CoM_{ML}) and vertical (CoM_V) directions were used as performance variables (Scholz and Schöner, 1999; Tokuda et al., 2017). Based on a previous study(Tokuda et al., 2017), a Jacobian matrix (*J*) was used to map the changes in elemental variables (segmental angles; Fig.1) to changes in the performance variable (CoM position). The kinematic model has 19 DoFs including ankle position, but the UCM calculations involve 16 DoFs because the CoM position is expressed with respect to the ankle, which is equivalent to fixing the XYZ coordinates of the ankle. Appendix2 represents the details of UCM equations to calculate V_{UCM}, V_{ORT}, and ΔVz. The UCM indices were averaged within the first 1/3 (early-swing), second 1/3 (mid-swing), and third 1/3 (late-swing) (Yamagata et al., 2018).

Statistical analyses

To test the differences between step lengths and mFH during lead- and trail-limb swing, paired t tests were performed for averages and variabilities of Lead_length, Trail_length, Lead_mFH, and Trail_mFH.

We performed MANOVA to evaluate the effects of *Limb* (Lead limb, Trail limb) and *Phase* (Early-, Mid-, and Late-swing) on UCM indices, CoM displacements, and CoM variabilities. When significant major effects or interaction were detected, we performed post hoc comparisons.

To test for conflation error in our three sub-phase analysis (i.e., error due to insufficient sampling frequency), we also performed statistical parametric mappings (SPM) analyses for UCM indices (Pataky et al., 2013). SPM is a generalization of classical hypothesis testing to the case where a dependent variable change over an n-dimensional domain; in this case n = 1, and that single dimension is time. SPM is rooted in Gaussian random field theory, which describes the probabilistic behavior of smoothly varying processes over these n-dimensional domains. Here we present three SPM results for differences between UCM indices during lead- and trail-limb swing: the "SPM{t}" (i.e., the temporal trajectory of the t statistic), the critical threshold at alpha=0.05 (i.e. the t value which a purely random, equally smooth Gaussian temporal process would exceed in only 5% of an infinite number of experiments), and suprathreshold cluster probability values (i.e., the probability that a purely random, equally smooth Gaussian temporal process would produce a suprathreshold cluster of the observed temporal extent); see Fig.4C for an illustration of these three components. We performed paired Hotelling's T2 tests as the main analysis (i.e., simultaneous analysis of the V and ML directions) and post hoc comparisons on single directions when significant differences were detected.

Pearson's comparisons were also performed to evaluate the relations of Lead_mFH (or Trail_mFH) with UCM indices during early-, mid-, late-swing phase of lead-limb (or trail-limb) swing, respectively.

Matlab 2020a software (Math Words Inc., MA, USA) was used for SPM analysis and SPSS software was used for the other analyses (Version 18, PASW Statistics, Chicago). The significance level was set at $p = 0.05$ except for Pearson's comparisons that used the method of Holm correction to adjust the p-values across the three swing phases (Chan et al., 2007).

3. Results

Participant characteristics

Table 1 lists the participants' physical characteristics. The step lengths and mFH of the lead and trail limbs are shown on Table 2. Lead_mFH was significantly greater than Trail_mFH, and Lead_length was significantly greater than Trail_length ($p < 0.01$). The average instants of obstacle crossing were 58.9 ± 4.5 % swing phase during lead-limb crossing and 37.8 ± 6.5 % swing phase during trail-limb crossing.

Figure2 shows the CoM averages and variabilities across subjects. In averaged CoM_{ML}, a significant *Limb* × *Phase* interaction (CoM_{ML} $F(2, 48) = 6.7$; $p < 0.01$; CoM_V $F(2, 48) = 13.0$; $p < 0.01$) was found. CoM_{ML} during mid lead-limb swing phase was significantly lower than that during early and late lead-limb swing, and during trail-limb swing, CoM_{ML} in early-swing was significantly greater than that in other phases. For both CoMv during lead- and trail-limb swing, the values in mid-swing were significantly greater than those in others. In CoM_{ML} variability, we found significant effects of *Limb* and *Phase* with no interaction (*Limb* $F(1, 24) = 17.2$; $p < 0.01$; *Phase* $F(2, 48) = 111.9$; $p < 0.01$). CoM_{ML} variability during lead-limb swing was significantly lower than that during trail-limb swing, and the significantly greatest variability was during late-swing, followed in order by early- and mid-swing. In CoM_V variability, a significant *Limb* × *Phase* interaction was found ($F(2, 48) = 11.0$; $p < 0.01$). CoM_V variability during late lead-limb swing was significantly greater than that during late trail-limb swing. During lead-limb swing, the variability during mid-swing was significantly lower than those during early- and late-swing, and during trail-limb swing, the variability during early-swing was significantly greater than those during mid- and late-swing.

UCM indices during lead-limb and trail-limb swing (Fig.3, 4)

Figure3 shows averaged V_{UCM} and V_{ORT} across subjects. V_{UCM} during mid-swing was significantly greater than that during the other phases in both ML (effect of *Phase*, $F(2, 48) = 30.5$; $p < 0.01$) and V directions (effect of *Phase*, $F(2, 48) = 24.4$; $p < 0.01$). There were no main effect of *Limb* and no interaction. In V_{ORT}, significant *Limb* × *Phase* interactions were seen in ML ($F(2, 48) = 38.1$, $p < 0.01$) and V ($F(2, 48) = 58.7$, $p < 0.01$) directions; in ML direction, V_{ORT} during early- and mid-phase of lead-limb swing were significantly greater than those during early- and mid-phase of trail-limb swing. Moreover, during lead-limb swing, V_{ORT} in late-swing was significantly greater than that in early- and mid-swing, and during trail-limb swing, V_{ORT} in late-swing was significantly lower than that in early- and mid-swing. In V direction, V_{ORT} during lead-limb swing were significantly greater than those during trail-limb swing through the phase, and V_{ORT} during late-phase of lead-limb swing was significantly greater compared to those during other phases of lead-limb swing.

Figure4A shows averaged ΔVz across subjects. Significant *Limb* × *Phase* interactions were found in ML ($F(2, 48) = 6.0$, $p < 0.01$) and V ($F(2, 48) = 15.3$, $p < 0.01$) directions; in ML direction, during lead-limb swing, ΔVz in late-swing was significantly lower than that in early- and mid-swing, whereas during trail-limb swing, ΔVz in early-swing was significantly lower than that in other phases. During early-phase, ΔVz during trail-limb swing were significantly lower than that during lead-limb crossing. In V direction, ΔVz during trail-limb swing were significantly lower than that during lead-limb swing through the phase. During lead-limb swing, ΔVz in late-phase was significantly lower than that in early- and mid-phases, whereas during trail-limb swing, ΔVz in mid-swing was significantly lower than that in other phases. During early- and mid-phases, ΔVz during trail-limb swing were significantly lower than that during lead-limb swing. In the results of SPM analysis, the differences in ΔVz between lead- and trail-limb swing were found around early- and mid-swing phases, similar to results of MANOVA, although conflation error was found around 90-100% swing phase (Fig.4C): the SPM results show significantly greater ΔVz was observed in the trail- vs. lead limbs (Fig.4C, 90-100%), but the opposite trend was observed in the late-swing results (Fig.4A). These contradictory results are explained by conflation: the inter-limb difference at the start of late-swing is much larger than the difference at the end of late-swing, making the former dominate the late-swing results in Fig.4A; in other words, in the Fig.4A results the early late-swing results are conflated with the late late-swing results. This suggests that three sub-phases are insufficient for characterizing late-swing effects in this dataset.

Relations between mFH and UCM indices (Fig.5)

There was no significant correlation between Lead-mFH and UCM indices during all phases of lead-limb swing. During all phases of trail-limb swing, Trail_mFH was positively correlated to V_{ORT} in V direction; V_{ORT} were increased with an increase in Trail-mFH (Fig.5; early-swing: $p = 0.002$, mid-swing: $p = 0.001$, late-swing: $p = 0.007$). The correlation coefficients were $r = 0.57$, $r = 0.58$, and $r = 0.49$, respectively. ΔVz during early trail-limb swing was negatively correlated to Trail-mFH ($p = 0.01$, $r = -0.47$); ΔVz decreased with an increase in Trail-mFH. There was no significant correlation between UCM indices in ML direction and Trail-mFH.

4. Discussion

The purposes of this study were to show the time differences of synergy index (ΔVz) for CoM position during obstacle crossing, and to reveal the relation of mFH with ΔVz during obstacle crossing. ΔVz in both directions during early- and mid-phases of trail-limb swing were lower than those during early- and mid-phases of lead-limb swing, and during trail-limb swing, ΔVz in early- and mid-phases were lower than those in other phases in both directions. We also found positive correlations of Trail_mFH with V_{ORT}, and negative correlations of Trail_mFH with ΔVz. This is the first study to investigate the temporal changes in synergy index for CoM position by segment configurations and to clarity whether high trail_mFH would affect the synergy index for CoM position.

In both directions, greater V_{ORT} and lower ΔVz during early trail-limb swing were seen than during lead-limb swing, implying that CoM position was not well controlled by a multi-joint kinematic synergy. The findings may be related to differences in motor control. During lead-limb crossing, since visual information can be used to control the body segments, suitable updating and strategy reorganizing can be conducted. On the other hand, during trail-limb crossing, we need to rely on memory for spatial characteristics of the obstacle (e.g., height, depth) and the accurate kinesthetic knowledge of swing foot position relative to the memory-mapped obstacle because of no visual information (Heijnen et al., 2014). Indeed, in V direction, an increase in ΔVz was found in the late-phase of trail-limb swing, and in results of SPM analysis, we even found greater ΔVz during 90-100% swing phase of trail-limb than those of lead-limb. Previous studies shown the risk of obstacle contacts with lead limb were higher than those with trail limb in older adults, unlike younger adults (Muir et al., 2020, 2015), implying the importance of evaluation during lead-limb crossing to prevent tripping. On the other hand, our results indicate that the control of CoM during early trail-limb swing may also be comparably important to consider in older adults.

In the ML direction, the CoM was well-controlled by kinematic synergies until lead limb obstacle crossing (59% swing phase on average), then the synergy index was low until around trail limb obstacle crossing (37% swing phase on average). CoM variables in the ML direction can be viewed as indices to assess the performance stability during obstacle crossing (Chou et al., 2003; Lee and Chou, 2006). As the large distance of CoM location from BoS (Chou et al., 2003; Huang et al., 2008; Lee and Chou, 2006), the ML control of CoM would be crucial from the latter phase of lead-limb swing until early phase of trail-limb swing. While the high risk of lateral fall is known during gait (Chou et al., 2003; Lee and Chou, 2006), our results augment these findings by clarifying the temporal context of this risk, and specifically that this risk is likely highest from late lead-limb swing until early trail-limb swing. This is partially unexpected because this high-risk window corresponds to double-stance phase, and not to obstacle tripping instants. Low ΔVz during those phases suggested low control of CoM position by adjusting multi-segments and low adjusting ability to unexpected perturbation (Hsu et al., 2013; Mattos et al., 2011), thus there is a possibility that balance recovery after trail limb tripping would be difficult at those phases.

In V direction, we found lower ΔVz around mid trail-limb swing, compared to other phases. A negative correlation between Trail_mFH and ΔVz during early trail-limb swing was also seen, indicating an increase in Trail-mFH was related to a decrease in control of

CoM positions by multi-segment synergy during early trail-limb swing. Given that early-swing phase is for a preparation of elevating the swing foot, the plan or preparation way to ensure the higher Trail_mFH before stepping over an obstacle in older adults would lead a decrease in ΔVz for CoM position. In other words, there is a possibility that older adults used multi-segment synergy to mainly make the sufficient Trail_mFH, thereby leading to low control of CoM position instead. While the primary variable relevant to the postural stability during gait is the mediolateral CoM position relative to BoS, the vertical CoM position is also relevant to the stability because horizontal external forces applied to the CoM produce larger moments about ankle joint. Our findings, especially the decreases in ΔVz to control CoM positions with an increase in foot elevations during early trail-limb swing, suggest that focusing on both the preparation phase and stepping over phase is necessary. Moreover, our results suggest that swing foot elevation and CoM position control should be coordinated for successful obstacle crossing in older adults. This is in agreement with a previous study that showed that patients with postural instability compensatorily increased postural sway to increase foot clearance (Galna et al., 2013).

It has been shown that insufficient foot elevation is related to a high risk of tripping. Earlier studies showed that the older adults used several conservative strategies to prevent falls during dynamic performances (e.g., walking and obstacle crossing), and especially during obstacle crossing, the strategy to highly elevate swing foot can be utilized to reduce tripping risk (Lu et al., 2006; Pan et al., 2016). Fall risks are related to both balance loss and tripping. Although the previous findings provide valuable information for representing motor control strategy, the measurements to show whether the strategy is harmful to control of whole body are required. If the patients excessively elevated the swing foot in a manner that is deleterious to CoM position control, a rehabilitation to correct the movements may be needed.

There were some limitations in this study. We did not consider CoM trajectories in the anteroposterior direction. Since the restraining a forward angular momentum of the body is needed for balance recovery after tripping or balance loss, evaluating the forward CoM trajectories is also important(Pijnappels et al., 2004).We used only an 8-cm tall obstacle, representing obstacles that are likely found in daily life. A previous study, however, shown that 2.5 % of body height (about 4 cm for the current subjects) is more useful to evaluate balance ability than 5% of body height (about 8 cm for the current subjects) (Chou et al., 2003). We acknowledge that a 4-cm tall obstacle might have been a better height to evaluate ΔVz. Also, mFH evaluated by the position of the second metatarsal might overestimate the foot clearance due to the motion of the ankle joint; however, we believe there are no effects on our results since the same variable was used among all subjects. Finally, it is unclear whether the low ΔVz for CoM position actually led to high risk of falls, and whether high ΔVz indeed helped with balance recovery following perturbation. A longitudinal study to investigate the relation between the ΔVz and future falls is needed.

5. Conclusions

We showed that kinematic synergies for CoM position are weaker during trail-limb swing compared to lead-limb swing, especially during early trail-limb swing. Also, the synergy became weaker with an increase in maximum foot height of the trail limb, indicating that conservative strategies with high trail foot elevation are not always helpful for successful obstacle crossing.

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Figure 1

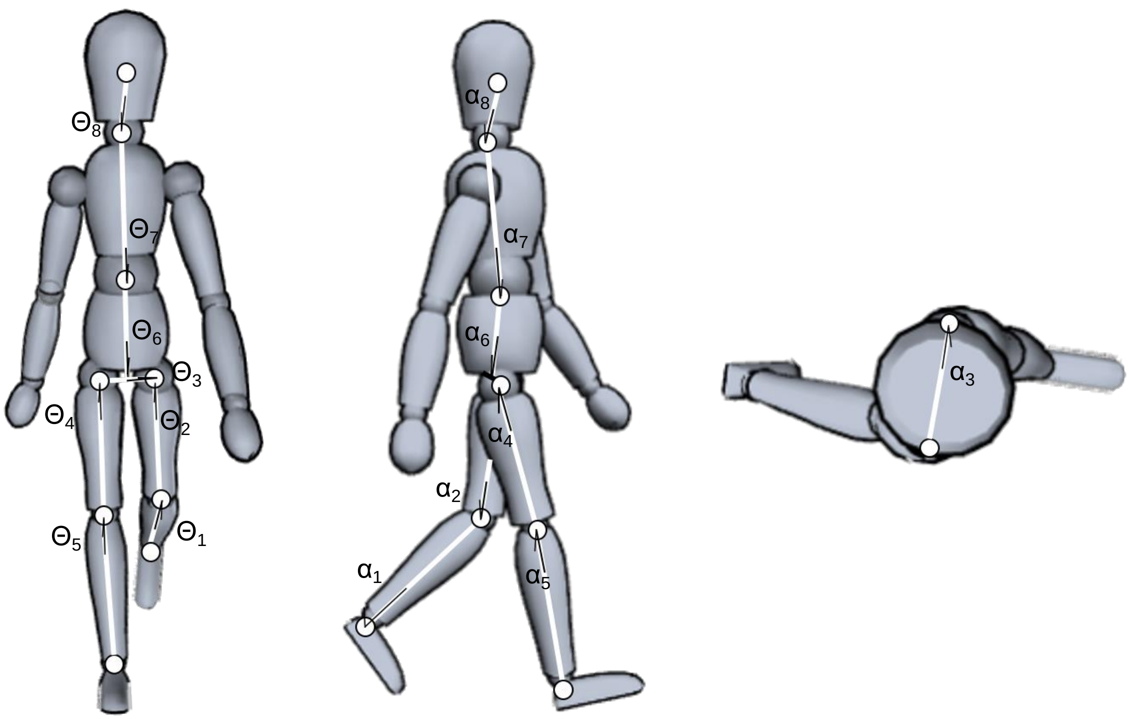


Fig 1. Illustration of the body segment angles

Eight body segments, i.e., both shanks, both thighs, pelvis, lower trunk, upper trunk, and head, were included for the geometric model. 8 degrees of freedom in the frontal sagittal plane (Θ_1: left shank, Θ_2: left thigh, Θ_3: pelvis, Θ_4: right thigh, Θ_5: right shank, Θ_6: lower trunk, Θ_7: upper trunk, Θ_8: head); 8 degrees of freedom in sagittal and transverse planes (α_1: left shank, α_2: left thigh, α_3: pelvis, α_4: right thigh, α_5: right shank, α_6: lower trunk, α_7: upper trunk, α_7: head).

Figure 2

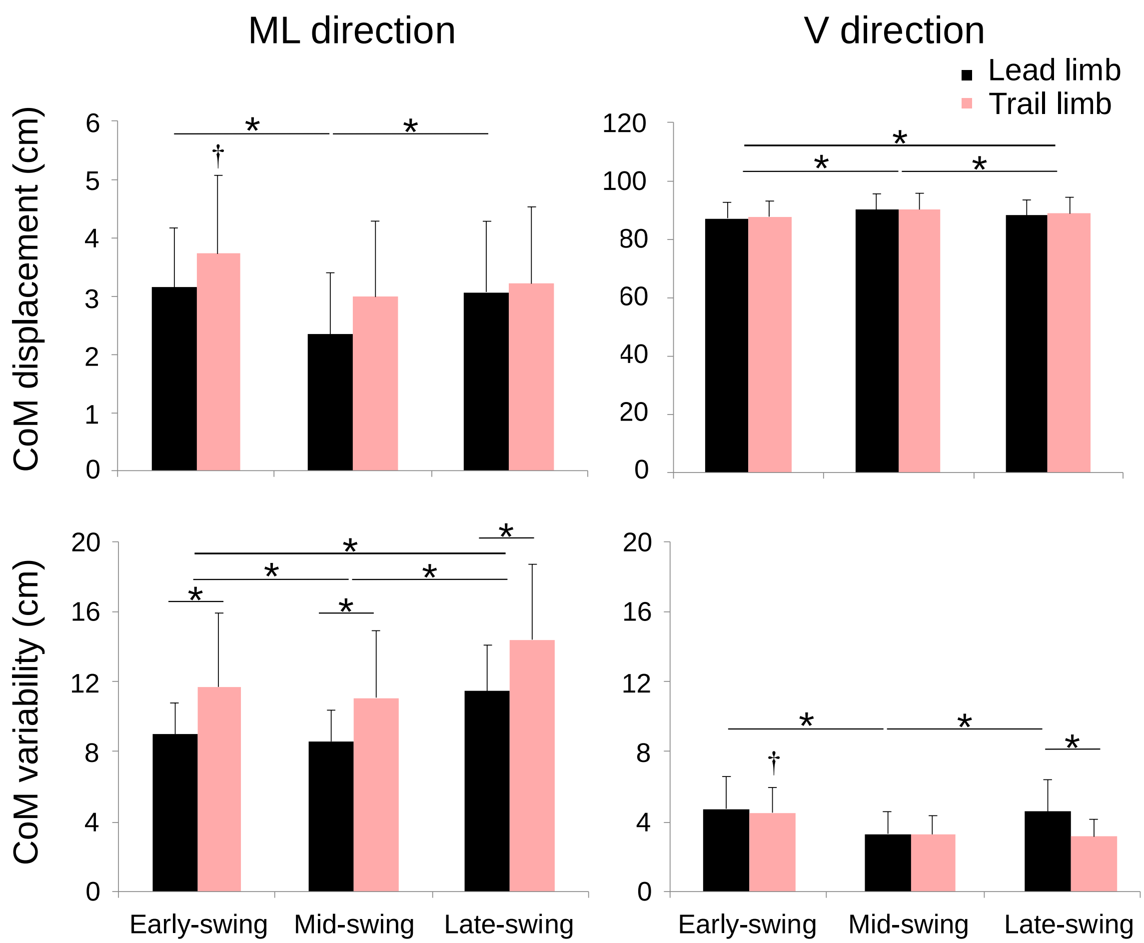


Fig 2. Averaged center of mass (CoM) displacements and variabilities: CoM displacements in the mediolateral (ML) (left panels) direction are based on the mediolateral distance from the joint center of the support ankle, and those in the vertical (V) (right panels) direction are based on the vertical distance from the ground. For CoM variabilities, standard deviation across repeated trials for subjects separately was averaged across subjects. * Significant differences ($p < 0.05$) between limbs; † Significant differences ($p < 0.05$) compared to other phases.

Figure 3

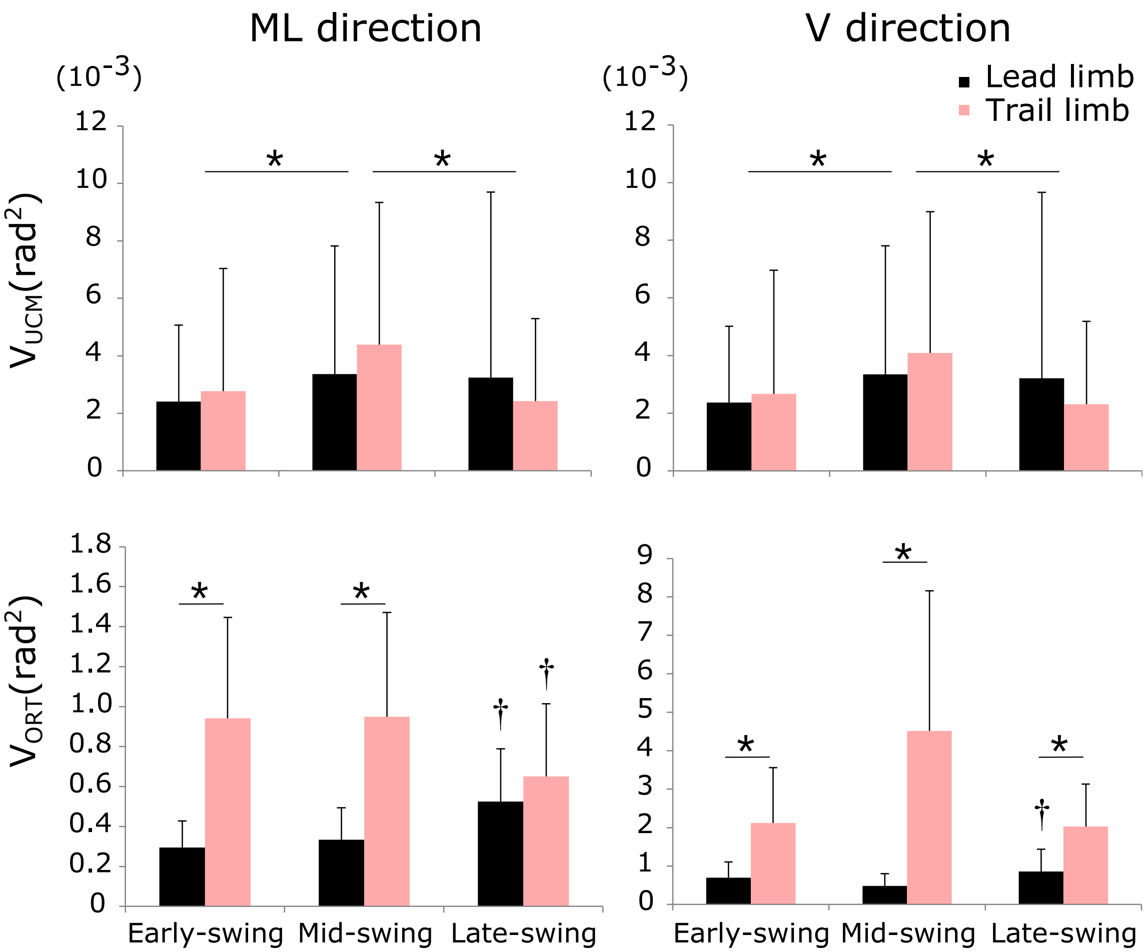


Fig 3. Averaged V_{UCM} and V_{ORT} across subjects: V_{UCM} that does not affect CoM trajectories and V_{ORT} that affects CoM trajectories are shown in the upper and lower panels, respectively. * Significant differences ($p < 0.05$) between limbs; † Significant differences ($p < 0.05$) compared to other phases.

Figure 4

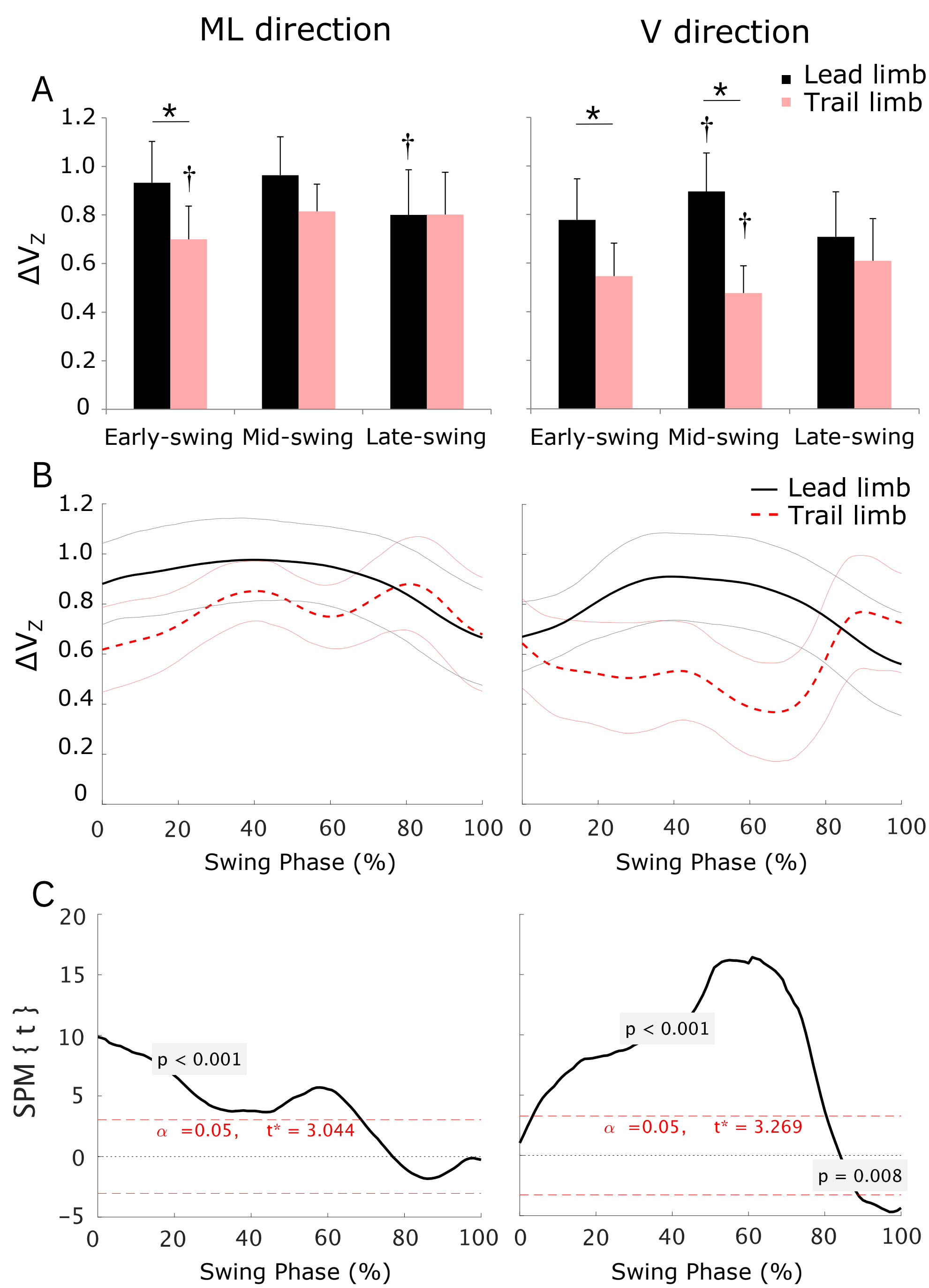


Fig 4. Fig4A: Averaged ΔV_Z across subjects during three phases, Fig4B: Time profiles of ΔV_Z cross-subject mean with standard deviation clouds, Fig4C: statistical parametric mapping (SPM) results; dotted horizontal lines represent the critical random filed theory threshold at α = 0.05.

Figure 5

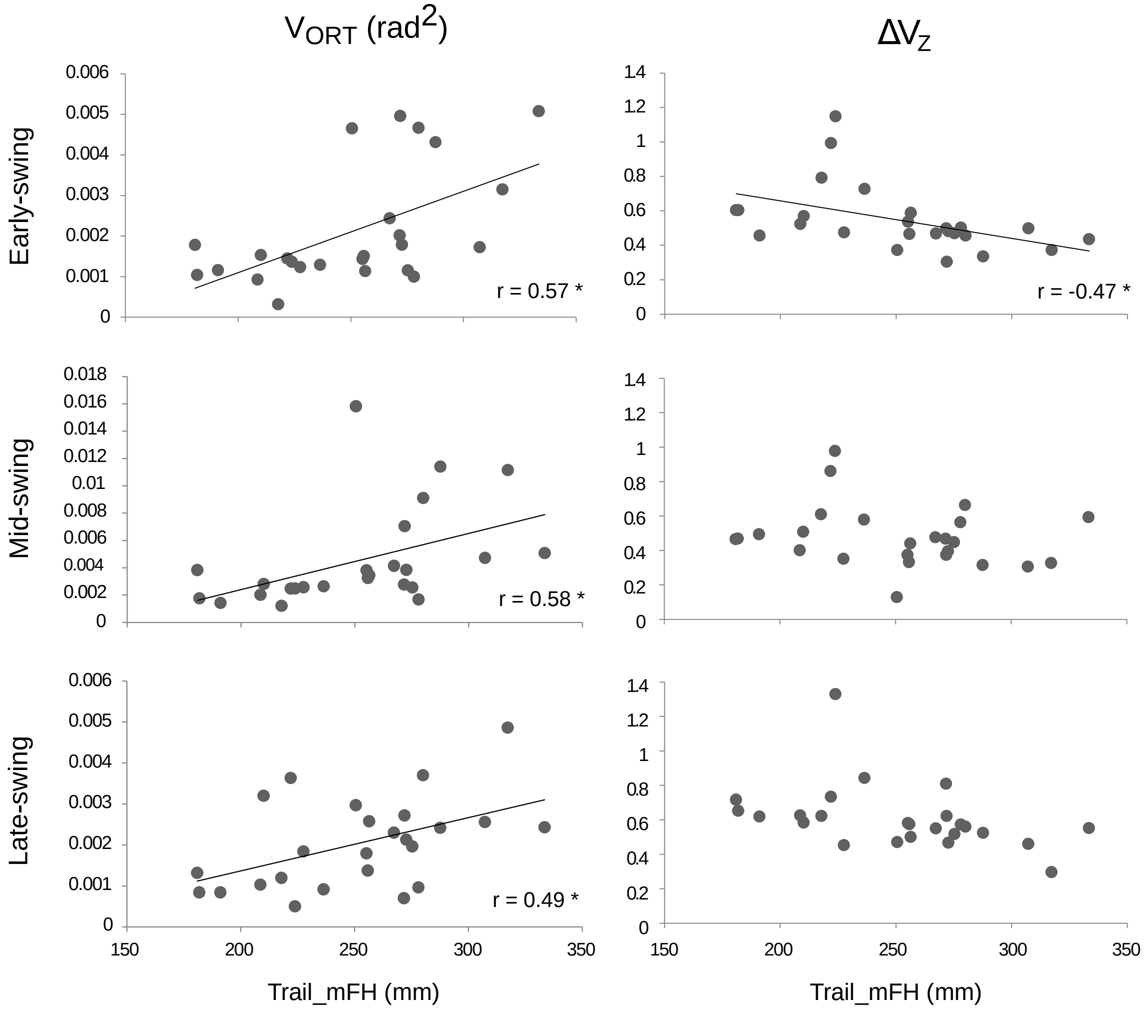


Fig 5. Correlations of trail limb foot clearance with V_{ORT} and ΔV_Z in the vertical direction: Correlations with V_{ORT} are shown in the left panels, and with ΔV_Z are shown in the right panels. * Significant correlations ($p < 0.05$) between foot clearance and UCM indices.

Table 1. Participant characteristics

Age (years)	75.6 ± 7.0
Height (m)	1.6 ± 0.09
Mass (kg)	57.6 ± 7.9
Walking speed (m/s)	1.0 ± 0.2

Table 2. Gait parameters

	Lead limb	Trail limb
Mean		
Step length (cm)	110.2 ± 15.0 *	105.4 ± 10.7
Foot clearance (cm)	25.6 ± 3.6 *	25.1 ± 4.1
Variability		
Step length (cm)	5.9 ± 2.6	4.8 ± 1.4
Foot clearance (cm)	1.5 ± 0.7	1.7 ± 0.8

*Significant differences ($p < 0.05$) between lead and trail limbs

APPENDIX

Appendix1

The purpose of this Appendix is to clarify the meaning of V_{UCM} and V_{ORT} in the context of relatively simple tasks.

Fig.A1 depicts a two-joint horizontal reaching tasks; to repeat moving fingertips from start to target points with a two-joint model.

As an example, two configurations of joint angles are shown at the target point. The dotted line depicts a sub-space (UCM) in joint space corresponding to the desired performance variable (fingertip position). In the top panels, the variance within the UCM that does not affect the performance variable (V_{UCM}) is greater than the variance orthogonal to the UCM that affects the performance variable (V_{ORT}), suggesting individual joint angles co-vary allowing the fingertip to reach the target; synergy. On the other hand, in the bottom panels, V_{UCM} is less than V_{ORT}, suggesting individual joint angles do not co-vary for successful reaching tasks.

Fig.A2 depicts a three-joint horizontal reaching tasks; to repeat moving fingertips from start to target points with a three-joint model.

Similarly to Fig.A1, two configurations of joint angles are shown at the target point. The dotted triangle area represents a sub-space (UCM) in joint space corresponding to the desired performance variable. In the top panels, V_{UCM} is greater than V_{ORT}, suggesting individual joint angles co-vary allowing the fingertip to reach the target, whereas, in the bottom panels, V_{UCM} is less than V_{ORT}, suggesting individual joint angles do not co-vary for successful reaching task.

In **Fig.A3**, two configurations are shown at two different timing with two- and three-joint models. In our study, UCM indices were calculated at every portion of the swing phase, similar to the example.

Fig.A1: UCM space (dotted line) in 2 dimensions

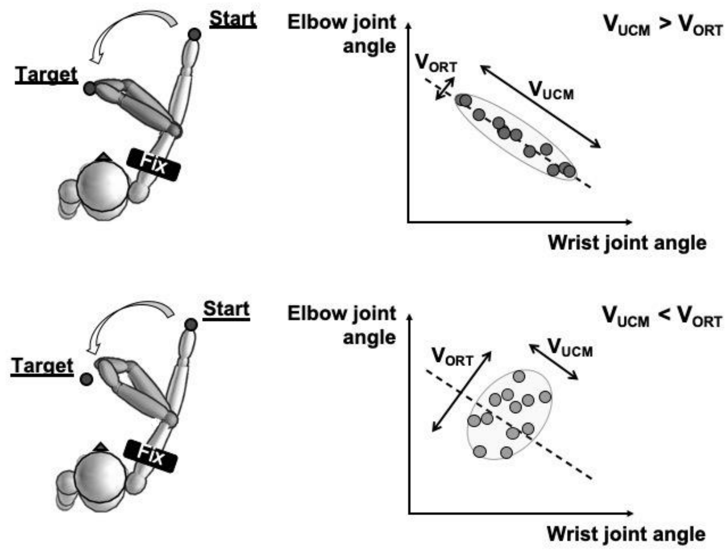


Fig.A2: UCM space (dotted triangle area) in 3 dimensions

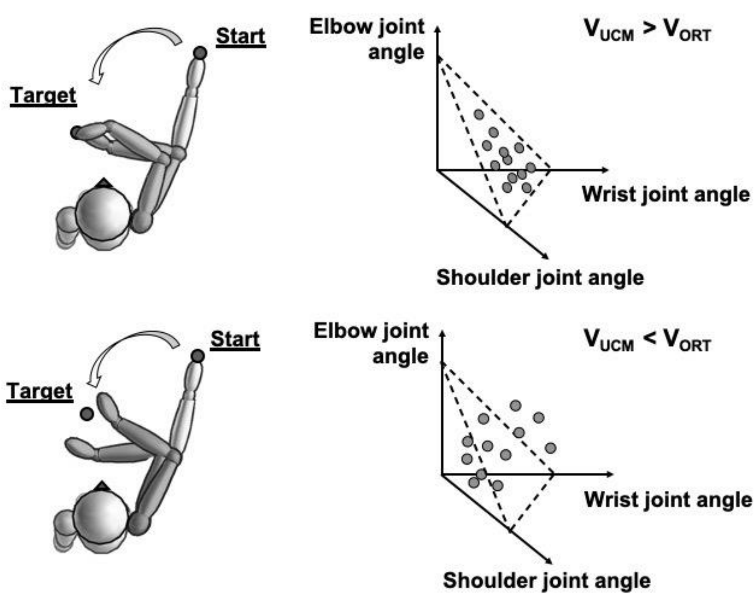
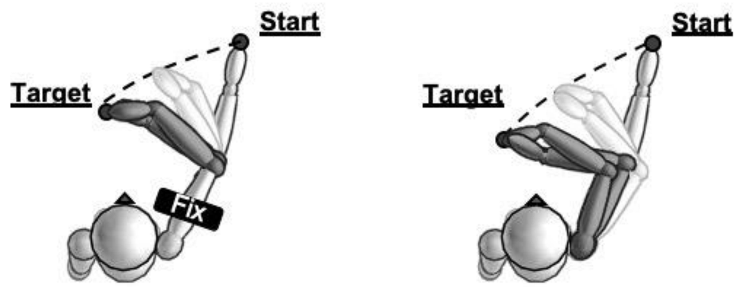


Fig.A3: Joint angles' contributions to instantaneous endpoint stability



Appendix2

The purpose of this Appendix is to clarify the equations of UCM analysis.

A Jacobian matrix (*J*) was used to map the changes in elemental variables to changes in the performance variable. *J* is the matrix of partial derivatives of changes in the trajectory of CoM position with respect to segmental angles, and the null space (ε) is the (*n*−*d*) vector represented by the dimensions in the segmental configuration space (*n* = 16) and CoM position (*d* = 1). At every portion of the swing phase, the differences between the segmental configurations (θ) and their mean ($\bar{\theta}$) were projected onto the null space

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

and the space orthogonal to the null space:

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

The variance in the segmental configuration that does not affect the CoM_{ML} or CoM_V (V_{UCM}) was calculated as the average of the squared length of θ_{UCM} across 20 steps, and normalized by the DoFs within the UCM subspace:

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

The variance in the segment configuration that affects the CoM_{ML} or CoM_{V} (V_{ORT}) was calculated as the average of the squared length of θ_{ORT} across 20 steps, and normalized by the DoFs within the orthogonal subspace:

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

ΔV was computed from V_{UCM} and V_{ORT} as below:

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

where

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

Fisher's *z*-transformation was applied to ΔV, referring to previous studies (ΔV_Z).