Local Dynamic Stability of the Locomotion of Lower Extremity Joints and Trunk Segment during Backward Upslope Walking

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Conflict of Interest Disclosure: None.

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Running Title: Gait stability during backward upslope walking

ABSTRACT

Backward slope walking was considered as a practical rehabilitation and training skill. However, its gait stability has been hardly studied, resulting in its limited application as a rehabilitation tool.

In this study the effect of walking direction and slope grade were investigated on the local dynamic stability of the motion of lower extremity joints and trunk segment during backward and forward upslope walking (BUW/FUW). The local divergence exponents (λ_S) of 16 adults were calculated during their BUW and FUW at grades of 0%, 5%, 10%, and 15%. Mean standard deviation over strides (MeanSD) was analyzed as their gait variability.

Backward walking showed larger λ_S for the abduction-adduction and rotational angles of knee and ankle on inclined surface than forward walking, while λ_S for hip flexion-extension angle at steeper grades was opposite. No grade effect for any joint existed during BUW, while λ_S increased with the increasing grade during FUW. As to the trunk, walking direction did little impact on λ_S. Still, significant larger λ_S for its medial-lateral and vertical motion were found at the steeper grades during both FUW and BUW.

Results indicate that during BUW, the backward direction may influence the stability of joint motions, while the trunk stability was challenged by the increasing grades. Therefore, BUW may be a training tool for the stability of both upper and lower body motion during gait.

Keywords: Backward slope walking, Local dynamic stability, Local divergence exponent, Gait analysis

INTRODUCTION

Backward slope walking (BSW), including backward upslope and backward downslope walking, combines the locomotion of backward walking and slope walking, and is supposed to be a more challenging task on the neuromuscular system (Lay, 2005; Lay et al., 2007). It is confirmed in physiological and biomechanical studies that, like backward level walking, BSW could not only provide better cardiovascular function, i.e. improved heart-rate, stroke-volume, cardiac output (Agbonlahor et al., 2009) and greater demands on EMG activity, including increased level of muscle activity of anterior tibialis during the entire gait cycle and of gastrocnemius between the phases of mid-swing to initial contact (Cipriani et al., 1995), but also facilitate gait balance, meanwhile, minimize force related to injuries (Bates & McCaw, 1986). On the other hand, compared to backward level walking, BSW has more advantages in exercising cardio-respiratory function and the lower extremity joints gradually and adequately by adjusting the grade (Agbonlahor et al., 2009; Hoogkamer et al., 2014), as the motor control system is predicted to require different walking strategies for slope walking (Lay et al., 2006; Sheehan & Gottschall, 2012). Thus, BSW has become a popular means of rehabilitation training for neurological impaired patients (Werner et al., 2002) or patients with a weak knee extensor (Agbonlahor et al., 2009; Cipriani et al., 1995).

When BSW is used for rehabilitation purposes, it is conceivable that greater challenges exist among the population with poor balance control ability, as high fall incidence occurs during walking backwardly (Laufer, 2005) or walking on slopes (Sheehan & Gottschall, 2012). The results of our previous investigation supported that the task of backward walking did reduce the local dynamic stability of the locomotion of lower extremity joints and trunk segment (Wu et al., 2015). Besides, the stability on the lower limb joints (Sheehan & Gottschall, 2012) and the trunk segment (Cromwell, 2003; Leroux et al., 2002; Vieira et al., 2017a) were also found to be reduced during upslope walking. To our knowledge, unfortunately, to date no study has reported gait stability during backward walking on inclined surfaces, leading to limited knowledge on how the motor control system responds to the dual effect of walking direction and slope grade. Thus, there is a need to evaluate gait stability during BSW in healthy participants, which is a pre-requisite for its application on future research concerned with pathological gait.

Gait variability measures are widely used in practice with proven success in predicting the probability of falling (Bruijn et al., 2013; Dingwell & Marin, 2006). The ‘variability’ usually refers to the amount of variation of a kinematic parameter over strides. It may quantify the spatial variation of stride, i.e. the magnitude of the variation. The increased gait variability was believed to be a sign of poor gait stability, which means that the gait system is incapable of accurately achieving the desired goal (Vieira et al., 2017b). The present study applied the local dynamic stability to reflect different properties of the walking dynamics from gait variability. It may quantify the temporal structure of stride variation. Unlike the gait variability that treats each gait cycle as independent, the local dynamic stability evaluates the evolution of stability over several strides (Vieira et al., 2017b). The local divergence exponent estimated from kinematic data (, e.g. joint angles and segment velocities) during a steady-state walking trial is a measure of local dynamic stability (Bruijn et al., 2013). It may quantify the sensitivity of the neuromuscular system to small perturbations during continuous walking, by characterizing how fast the neighboring trajectories of a reconstructed state space diverge after a small perturbation (Bruijn et al., 2012). The larger local divergence exponents are corresponded to a poorer ability of balance recovery. The local divergence exponent calculated from strides over a shorter period (one stride cycle, labeled λ_S) is used to forecast the probability of falling during walking. The construct, predictive and convergent validity of λ_S was found to be better supported in falling prediction (Bruijn et al., 2013).

This study aimed to estimate the local dynamic stability of the locomotion of lower extremity joints and trunk segment during backward upslope walking (BUW). Here, we treated the measures of the trunk segment and lower extremity joints as independent 'locomotion systems', so as to obtain an exact state estimate of walking by numerical methods. Therefore, we calculated the short-term local divergence exponents (λ_S) for the joints and the segment. We then tested the effect of walking direction by comparing the stability during BUW with forward upslope walking (FUW) at the same grade; and the effect of slope grade by comparing the stability at different grades during BUW and FUW, respectively. The mean standard deviation (MeanSD) was further quantified as the amount of gait variability to provide more insight into the effect of walking direction and slope grade on the gait stability (Lay, 2005; Lay et al., 2006; Leroux et al., 2002). The gait stability was found to be challenged during backward walking (Wu et al., 2015) and slope walking (Cromwell, 2003; Sheehan & Gottschall, 2012). Therefore, we hypothesized that compared to FUW, the local dynamic stability and the stride-to-stride gait variability of the lower extremity joint (, i.e. the hip, the knee and the ankle) angles and the trunk segment velocity were worse during BUW (, i.e. λ_S and MeanSD for the joint angles and segment velocity would be larger,) and would be further challenged by the increasing grades.

METHODS

Participants

Sixteen young adults (nine male, seven female; age 23.8 ± 1.4 years; height 1.69 ± 0.04m, BMI 20.46 ± 2.50 kg/m^2) were recruited for the study. None of the participants reported orthopedic or neurological injuries or disorders that could affect gait, and all of them were capable of ambulating independently without any assistive device. The experimental protocol was reviewed and approved by the Institutional Review Board at Biomedical Engineering School of Shanghai Jiao Tong University and the informed consent was obtained from each participant before the scheduled test date.

Experimental Protocol

For familiarization, the participants were habituated to the walking area on a treadmill (F80 Sole Fitness, Jonesboro, AR, USA) in a backward and forward upslope way (BUW/FUW) at each of four grades (0%, 5%, 10%, 15%). The running surface of the treadmill was 56 cm×152 cm in size with no force sensor installed. The participants may practice each walking condition for 5 minutes with at least 5 minutes rest before the data collection began. The tasks of downslope walking were not included in this study. During pilot tests, most participants complained such tasks were too difficult, and they were afraid of those tasks especially in a backward direction on a treadmill. Thus, the participants were only allowed to walk upwards at gentle grades with their preferred walking speed (PWS). The PWS in each walking direction at each grade was determined following a previously reported protocol (Dingwell & Marin, 2006). During the experiment, the participants completed a 5-min walking trial under each walking direction at four grades with PWS. All participants were blinded to their exact walking speeds throughout the experiment. These trials with different walking conditions were performed in a randomized order for each participant. The participants were asked not to hold or touch the treadmill handles by hands or by other body parts during walking. They were allowed a break of minimum 3 minutes between trials.

An 8-camera motion capture system (Vicon T40, Oxford Metrics, Oxford, UK) operating at 100 Hz was used to record the participants' body movement by capturing the refined Cleveland Clinic Marker set including forty-two reflective markers placed on each participant. The four rigid clusters each consisted with four tracking markers were respectively attached in the middle part of the thighs and shanks of both sides. The anatomical markers were placed on the relevant locations of the lower extremity joints and trunk landmarks. (**Figure 1**)

[Insert **Figure 1**]

Data Processing

Marker kinematics were low-pass filtered with a cut-off frequency of 10Hz using a fourth-order and zero-lag Butterworth filter prior to data analysis. We included 100 consecutive strides for quantifying the local dynamic stability and gait variability based on the angle of hip, knee and ankle joint in the motion of flexion–extension (FE), abduction/adduction (AB/AD) and internal/external rotation (RT), as well as the linear velocity of the trunk segment in the motion of anterior-posterior (AP), medial-lateral (ML) and vertical (VT) (**Figure 2 (a)**). The angles were calculated by using Visual3D software (v5 Professional, C-Motion Inc., USA). The linear motion of the trunk segment was defined using a virtual center marker, defined as the average location of the four markers: *clavicle*, *sternum*, *7th cervical vertebrae*, and *10th thoracic vertebrae* (**Figure 1**).The data of strides calculated during BUW and FUW both began and ended at foot contact. Foot contact was identified as the intra-stride maximum of the heel marker in anterior-posterior (AP) direction during both FUW and BUW.

Local Dynamic Stability

The local dynamic stability of the above joint angles and trunk velocity was characterized by the local divergence exponents (λ_S). Time series were time-normalized to 10 thousand samples to eliminate the effect of time series length on the calculation of local divergence exponents (Bruijn et al., 2013) (**Figure 2 (b)**), using a shape-preserving interpolation predefined in MATLAB (Version R2012a, The MathWorks, Inc., USA). This interpolation is based on a cubic spline using not-a-knot end conditions. The interpolated value at a query point is based on a cubic interpolation of the values at neighboring grid points. Meanwhile, the stride-to-stride temporal variations were preserved by leaving the number of data points during each stride unnormalized. We reconstructed a 5-dimensional state space from the time-normalized time-series using a constant delay of 10 samples (**Figure 2 (c)**). The embedding dimension was determined by the global false-nearest-neighbor analysis, while the selected time delay was estimated using the first minimum of the average mutual information function. The local divergence exponents were calculated according to the algorithm described by Rosenstein et al (Rosenstein et al., 1993). In the reconstructed state space, all pairs of the nearest neighboring points were identified, and the Euclidean distances between the nearest neighbors were calculated and tracked until the end of the time series. A time vs. the Euclidean distance curve representing the average logarithmic rate of Euclidean distances (i.e. the divergence) over all original nearest neighbor pairs then can be obtained. The local divergence exponent was calculated as the slope of the curve. In our study, we expressed the rate of divergence across the span of 0-0.5 stride, i.e. the short-term divergence exponent, λ_S (**Figure 2 (d)**).

[Insert **Figure 2**]

Gait Variability

The stride-to-stride variability of the above joint angles and trunk velocity was determined by calculating the mean standard deviations (MeanSD). Data within the given strides were time-normalized into 101 samples (0–100%) per stride (**Figure 3 (a)**). The standard deviation over the included 100 strides for each sample was calculated (**Figure 3 (b)**). MeanSD was determined as the averaged value of the standard deviations over all percent of the gait cycle.

[Insert **Figure 3**]

Statistical Analysis

The generalized estimating equations (GEE), a regression technique taking repeated measures into account (Liang & Zeger, 1986), was used to determine the significant effect of walking direction (with two levels: FUW and BUW) and slope grade (with four levels: 0%, 5%, 10%, and 15%) on local dynamic stability and stride-to-stride variability. PWS of each participant was included during GEE as a covariate to exclude the effect of walking speed. (the dependent variables: λ_S/MeanSD, respectively, the covariate: PWS, and the independent variables: walking direction/slope grade). The homogeneity of regression slopes was tested by checking the significance of the interaction between PWS and walking direction/slope grade, respectively. The simple effect of direction within different grade conditions, as well as the grade effect within different direction conditions would be checked respectively. The effects of direction and grade on PWS and stride length were additionally checked by two-way repeated measures ANOVA. All *post hoc* multiple comparisons were performed using Bonferroni adjusted *t* tests. Linear regression analysis was used to test the relationship between PWS and λ_S, as well as between PWS and MeanSD, respectively. The relationship between the λ_S and the MeanSD was also tested by the same analysis. Significant level *p* of all tests was chosen as .050. All data were processed by SPSS Statistics software (Version 17.0, SPSS Inc., USA).

RESULTS

PWS and Stride Length during BUW

The PWS was significantly affected by the walking direction ($p < .050$). Compared to FUW, a smaller PWS was found during BUW at each grade (**Table 1**). As for the effect of slope grade, the PWS during both FUW and BUW at steeper grades were smaller than at gentler ones ($p < .050$, respectively). There was no walking direction effect on stride length ($p > .050$), while significant grade-related differences existed in both BUW and FUW conditions ($p < .010$, respectively). Smaller stride length was observed at steeper grades during both BUW and FUW. No interaction between directions and grades existed in PWS and stride length ($p > .100$, respectively).

[Insert **Table 1**]

Local Dynamic Stability during BUW

Effects of Walking Direction on λ_S

λ_S for the lower extremity joint angles and the trunk velocity were significantly affected by the walking direction (**Figure 4** and **Table 2**). Compared to FUW, larger λ_S for the knee AB/AD angle at 0%, 5% grades and the ankle AB/AD angle at all grades displayed during BUW ($p < .050$, respectively). Significant larger λ_S was also shown in RT angle of all joints and in the trunk VT velocity during backward level walking than during the forward condition ($p < .050$), respectively. An exception was the hip FE angle, where significant smaller λ_S was found during BUW at 10% and 15% grades ($p < .050$, respectively).

Effects of Slope Grade on λ_S

For lower extremity joint angles, no grade effect on λ_S existed during BUW ($p > .010$) **(Figure 4)**. Meanwhile, λ_S for all joint angles increased with the growing grades during FUW. In all motion directions, λ_S for the hip angles at 0% and 5% grade were significantly smaller than at steeper grades during FUW ($p < .050$, respectively). Similarly, the knee and ankle angles during FUW displayed smaller λ_S at 0%, 5% grade than at 15% grade ($p < .050$, respectively). λ_S for the trunk velocity significantly increased with the growing grades during FUW and BUW. In both walking directions, the trunk ML velocity displayed smaller λ_S at 0%, 5% grade than at 15% grade, while pairwise difference among all four grades were significant in the VT velocity that a smaller λ_S was observed at the gentler grade ($p < .050$, respectively). No interaction was found between walking directions and slope grades in λ_S ($p > .050$) (**Table 2**).

[Insert **Figure 4**]

[Insert **Table 2**]

Gait Variability during BUW

Effects of Walking Direction on MeanSD

For different joint angles, the effects of walking direction on MeanSD were variously presented (**Figure 5**). The MeanSD for the hip FE angle and the knee FE, AB/AD angle during BUW were smaller than during FUW at 10% and 15% grade ($p < .050$, respectively). Significantly larger MeanSD were found in ankle joint angle at all grades during BUW than during FUW ($p < .050$, respectively). As to the trunk velocity, compared to FUW, the MeanSD during backward level walking were larger in all motion directions ($p < .050$, respectively).

Effects of Slope Grade on MeanSD

There were significant interaction effects on MeanSD between walking directions and slope grades in the hip and knee FE angles ($p < .050$, respectively) (**Figure 5**). During FUW, the MeanSD for these two joint angles at 10% and 15% grade were larger than those at gentler grades, while the grade effects were just the opposite during BUW ($p < .050$, respectively). Compared to gentler grades, significantly larger MeanSD at 10% and 15% grade were also found in the knee AB/AD joint angle during FUW ($p < .050$, respectively). No grade related difference was found in the RT angle of any joint during either BUW or FUW ($p > .050$). As to the trunk velocity, the grade effect only existed during FUW. The MeanSD in AP and ML motion during forward level walking were significantly smaller than during slope, while significant pairwise difference existed among almost all grades in the VT velocity that a smaller MeanSD was observed at the gentler grade ($p < .050$, respectively).

[Insert **Figure 5**]

Relationship between PWS and λ_S / MeanSD

For both walking directions, PWS showed a significant negative relationship with λ_S in all motion directions of the joint angles and the trunk velocity ($p < .001$, respectively). (**Table 3**) The relationship between PWS and λ_S for the trunk segment in AP direction of a particular participant was further displayed as scatterplots. (**Appendix Figure**)

[Insert **Table 3**]

Whether during FUW or BUW, there was no significant relationship between PWS and MeanSD in any motion direction of the joint angles and the trunk velocity ($p > .100$, respectively). **(Table 4)**

[Insert **Table 4**]

Relationship between λ_S and MeanSD

During BUW, λ_S showed a significant negative relationship with the MeanSD in all motion directions of the lower extremity joint angles, and the trunk velocity in AP motion as well ($p < .010$, respectively). Positive correlations were found in all motion directions of both lower extremity joint angles and the trunk velocity ($p < .010$, respectively) during FUW, except for the RT angle of the lower extremities ($p = .070$) (**Table 5**).

[Insert **Table 5**]

DISCUSSION

In our previous investigation, compared to forward walking, gait stability during backward walking was shown to be challenged (Wu et al., 2015). On the other hand, walking on the inclined surfaces was also found to decrease local dynamic stability particularly in upslope conditions (Vieira et al., 2017a). Unfortunately, as far as we knew, to date no study has reported gait stability during backward walking on inclined surfaces. This was the first time that the dual effects of the walking direction and slope grade on the gait stability of the joint and segment motions were investigated, aiming to predict whether the gait stability would be challenged during BUW, so as to examine whether BUW would be a promising tool to train gait stability.

It was consistent with the original hypothesis that, backward walking did negatively influence the local dynamic stability of the human locomotion on inclined surface. This may be explained by the fact that during backward walking, the subject lacks the visual information to process, and fears bumping and falling because backward walking is not habitually performed (Nadeau et al., 2003). Consequently, compared to walking forwards, a reduced walking speed (, which was validated in the present study,) and a greater effort were required for the neuromuscular system to control lateral oscillations of the body when walking backwards (Nadeau et al., 2003). In our study, this effect of walking direction was especially significant for the AB/AD angles of the knee and ankle joint, as these joints showed worse local dynamic stability during backward walking. Our previous unpublished results on the total range of motion showed that values of the knee and ankle AB/AD angle during BUW were significantly smaller compared to FUW ($p < .050$, respectively). (See **Appendix Table**) This postural adaption may induced by the greater control imposed on the knee and ankle joint demonstrated by increased muscle activity (Katsavelis et al., 2010), so as to overcome the worse stability of the joint motion and avoid falls during BUW. In our study, compared to BUW, a reduced local dynamic stability in hip FE angle was identified during FUW. We speculated the hip joint during FUW needed to expend more control effort to stabilize its motion, which was similar to the kinetic demands for knee joint during BUW. These results could be supported by Lay et.al that (Lay, 2005), a larger moment and higher power in the hip FE joint motion were found during FUW in comparison with BUW, while the opposite effect of walking direction was observed on the kinetic data of the knee joint. Backward walking direction did little impact on the stability of the trunk motion in the present study. This might be due to the stabilization strategy adopted by the trunk segment, that during backward walking the trunk was supposed to adopt a generally rigid functioning with (, i.e. rigidly linked to) the underlying supporting segment in both sagittal and frontal plane (Nadeau et al., 2003). Our results thus further prove the effectiveness of the trunk stabilization strategy during BUW.

The effect of the slope grade on the local dynamic stability of the lower extremity joint motion was significant during FUW, where the stability of all joints reduced as the grade increased. This was mostly concordant with the grade-related difference in MeanSD of FE and AB/AD motion, which was further supported by the positive correlation between λ_S and MeanSD during FUW. Results in previous studies were consistent with ours as well, that in comparison with level walking, (forward) slope walking would reduce the gait stability in both sagittal and frontal plane, thus resulting in a greater fall risk (Gottschall & Nichols, 2011; Sheehan & Gottschall, 2012). These results indicate that the active control is required to stabilize the lower extremity joints in all motion directions during slope walking. In order to raise the center of mass (COM) and prevent falling on the inclined surfaces, the motor control system needs to handle the altered vertical foot displacement and its clearance, as well as the higher horizontal friction demands compared to the level walking (McIntosh et al., 2006). All these changes of walking pattern may explain the observed effect of slope grade on the gait stability of the lower extremity joints. Meanwhile, for BUW conditions, there was no grade-related difference in λ_S for any joint. In our study, significant negative correlations between λ_S and MeanSD were found in all angular motions during BUW, indicating that these two metrics responded oppositely to the changes of the slope grade under backward walking conditions. For example, the gait variability (indicated by the value of MeanSD) of the knee joint even attenuated with the increasing grades during BUW, while the local dynamic instability (indicated by the value of λ_S) slightly increased. These results further supported that measurements of local dynamic stability and gait variability quantify fundamentally different properties of walking dynamic (Dingwell & Marin, 2006; Vieira et al., 2017a). Here, a possible interpretation is that, to accommodate BUW, a demanding walking task that accompany backward direction and inclined surface, the motor control system may reduce and control the gait variability (, i.e. the spatial variation of consecutive strides) of the knee joint angle, in exchange for its moderate increasing local dynamic instability (i.e. with no significantly-changed temporal structure of stride variation) (Dingwell & Marin, 2006).

The local dynamic stability of the trunk motion was quite sensitive to grade-related differences. A challenged stability of the trunk ML and VT motion was found at the steeper inclined surface under both FUW and BUW conditions. It supported the finding by Kang et al., that the trunk motion is a more sensitive marker of impaired gait function compared to lower extremity joints (Kang & Dingwell, 2009). The gait stability in medial-lateral direction is important for controlling body balance and predicting falls (Bauby & Kuo, 2000; Maki & Mcilroy, 2006), therefore our results indicated that compared to level walking, upslope walking may impose more challenges on the gait stability in both forward and backward walking direction in an effective way. Furthermore, our finding was well consistent with the previous study on FUW (Vieira et al., 2017a), that our measurements of the local dynamic stability and gait variability showed a similar trend with the increasing grades. Still, since the trunk stability displayed no significant direction-related difference, there was no extra challenge on the trunk stability during BUW compared to FUW.

Additionally, we found no significant interaction effect on λ_S. Therefore, we consider that upslope walking in both directions may be promoting tools to train local dynamic stability, as the expected performance of the rehabilitation can be achieved by setting customized grades of the walking surface. Moreover, BUW under safe conditions (, e.g. with harness) may be an alternative advanced strategy for future training on gait stability. It may show improvements for the stability of both upper and lower body motion (, e.g. for elderly), which remains to be shown during normal walking.

There were several limitations in this study. The healthy young participants walked at a relatively lower speed on the treadmill. We attribute it to the fact that these participants walked barefoot on treadmill, so that their foot motion can be tracked more accurately. Another fact is that, no safety harness was applied for our participants, which made them a bit worry and slow down during the experiment. To exclude the effect of walking speed indicated by **Table 3** and **Table 4**, in present study, PWS was considered as a covariate during the statistical analysis. Additionally, the participants were asked to walk upward on the treadmill at gentle grades, as this walking condition is a safer and more common activity of daily living. Still, walking on steeper slopes may be used as a perturbation of normal locomotion (Lay, 2005; Lay et al., 2007), so that the capacity of the joint/segment to recover from this perturbation can be further investigated. When safety is secured (, e.g. with a harness), the downward slope walking should also be investigated in future work to provide more insight into its gait stability, and can be considered as a promising training condition as well. More pre-experiment trainings may help the participants overcome not only the difficulties in practical experience but also the fear of falling. Furthermore, a larger study could be proposed to examine whether applying speed constrains during training may provide a challenge for gait stability among the elderly or patients during BSW as the BSW is frequently prescribed for those specific populations as a rehabilitation treatment.

CONCLUSIONS

The local dynamic stability of the human locomotion during upslope walking was challenged by the backward walking direction or increasing slope grades. As for BUW, the backward walking direction challenged the local dynamic stability of the motion of lower extremity joints, while the increasing grade imposed large challenges on the stability of the trunk motion. Therefore, BUW can be considered as a training tool for the stability of both upper and lower body motion during gait.

FUNDING

This study was supported by the National Nature Science Foundation of China (Grant No. 31170901) and Key Technology Support Project of Shanghai Municipal Science and Technology Commission (Grant No. 16441908200 and 13441902900).

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Tables

Table 1 PWS and stride length during FUW and BUW at 0% -15% grade, mean (SD)

	FUW				**BUW**			
	0%	**5%**	**10%**	**15%**	**0%**	**5%**	**10%**	**15%**
PWS (m/s)	0.73	0.72	0.71	0.71	0.49	0.47	0.47	0.47
	(0.10)	(0.09)	(0.07)[a]	(0.08)[b]	(0.05)[#,c]	(0.05)[#]	(0.09)[#]	(0.06)[#]
Stride length (m)	0.83	0.81	0.75	0.74	0.80	0.79	0.77	0.74
	(0.17)	(0.16)	(0.12)[a]	(0.13)[b]	(0.11)	(0.13)	(0.12)	(0.12)[d]

[#] $p < .050$ for FUW compared to BUW within the grade condition

[a] $p < .050$ for 0%, 5% grade compared to 10% grade within the direction condition

[b] $p < .050$ for 0%, 5% grade compared to 15% grade within the direction condition

[c] $p < .050$ for 0%grade compared to 5%, 10% and 15% grade within the direction condition

[d] $p < .050$ for 0%, 5% and 10% grade compared to 15% grade within the direction condition

Table 2 Results of statistical analysis for the effect of walking direction/slope grade on λ_S

		Effect of walking direction		**Effect of slope grade**		**Interaction effect**	
		***F* (1 , 15)**	***p***	***F* (3 , 45)**	***p***	***F* (3 , 45)**	***p***
Hip	FE Angle	5.01	.026*	3.39	.020*	2.11	.102
	AB/AD Angle	0.79	.370	5.75	.001*	0.69	.560
	RT Angle	4.68	.047*	6.87	< .001*	1.19	.315
Knee	FE Angle	3.28	.064	2.99	.043*	0.99	.398
	AB/AD Angle	9.13	.009*	5.97	< .001*	2.48	.064
	RT Angle	7.12	.015*	5.58	.002*	0.56	.642
Ankle	FE Angle	3.81	.053	1.89	.138	0.15	.928
	AB/AD Angle	16.47	.001*	2.89	.048*	0.72	.544
	RT Angle	6.23	.024*	2.87	.049*	1.58	.198
Trunk	AP Velocity	2.05	.147	2.96	.044*	0.26	.851
	ML Velocity	0.58	.446	4.28	.006*	0.05	.985
	VT Velocity	5.30	.033*	16.55	< .001*	0.67	.571

*$p < .050$ was set as significant level

Table 3 Relationship between PWS and λ_S with the intercept (*a*), regression coefficients (*b*) and their standard errors (s.e.)

			λ_S		
			a **(s.e.)**	***b*** **(s.e.)**	***p***
PWS during FUW (m/s)	Lower extremity joints	FE angle	3.560 (0.123)	-1.719 (0.154)	<.001*
		AB/AD angle	3.251 (0.133)	-1.717 (0.166)	<.001*
		RT angle	2.645 (0.124)	-1.416 (0.156)	<.001*
	Trunk	AP velocity	3.774 (0.169)	-1.850 (0.211)	<.001*
		ML velocity	3.169 (0.238)	-1.458 (0.298)	<.001*
		VT velocity	2.970 (0.209)	-1.445 (0.263)	<.001*
PWS during BUW (m/s)	Lower extremity joints	FE angle	3.578 (0.149)	-1.753 (0.191)	<.001*
		AB/AD angle	3.358 (0.130)	-1.695 (0.166)	<.001*
		RT angle	3.088 (0.173)	-1.466 (0.221)	<.001*
	Trunk	AP velocity	3.889 (0.292)	-1.815 (0.367)	<.001*
		ML velocity	3.670 (0.261)	-1.524 (0.334)	<.001*
		VT velocity	2.899 (0.252)	-1.310 (0.322)	<.001*

The models used was $\lambda_S = a + b \times \text{PWS}$

* Significant relationship between walking speed and local dynamic stability ($p < .050$)

Table 4 Relationship between PWS and MeanSD with the intercept (*a*), regression coefficients (*b*) and their standard errors (s.e.)

			MeanSD (Deg or m/s)		
			***a* (s.e.)**	***b* (s.e.)**	***p***
PWS during FUW (m/s)	Lower extremity joints	FE angle	2.133 (0.539)	0.253 (0.800)	.329
		AB/AD angle	1.276 (0.282)	0.122 (0.354)	.731
		RT angle	1.171 (0.643)	0.205 (0.257)	.134
	Trunk (×10^{-2})	AP velocity	3.144 (0.857)	1.207 (1.076)	.267
		ML velocity	2.166 (0.683)	1.300 (0.879)	.146
		VT velocity	1.983 (0.643)	1.257 (0.811)	.128
PWS during BUW (m/s)	Lower extremity joints	FE angle	2.918 (1.002)	0.677 (1.283)	.598
		AB/AD angle	1.146 (0.559)	0.515 (0.716)	.473
		RT angle	1.298 (0.232)	0.685 (0.301)	.024
	Trunk (×10^{-2})	AP velocity	3.728 (0.918)	1.380 (1.176)	.247
		ML velocity	2.010 (0.725)	1.360 (0.939)	.155
		VT velocity	1.562 (0.891)	1.487 (1.161)	.207

The models used was MeanSD = *a* + *b* × PWC

* Significant relationship between walking speed and gait variability ($p < .050$)

Table 5 Relationship between λ_S and MeanSD with the intercept (*a*), regression coefficients (*b*) and their standard errors (s.e.)

			MeanSD		
			a **(s.e.)**	***b*** **(s.e.)**	***p***
λ_S during FUW	Lower extremity joints (Deg)	FE angle	2.064 (0.847)	0.687 (0.227)	< .001*
		AB/AD angle	2.085 (0.245)	0.374 (0.126)	.003*
		RT angle	2.401 (0.210)	-0.397 (0.112)	.070
	Trunk ($m/s\times10^{-2}$)	AP velocity	6.769 (1.136)	0.809 (0.372)	< .001*
		ML velocity	2.609 (1.294)	0.246 (0.081)	.004*
		VT velocity	0.628 (0.092)	1.323 (0.460)	.006*
λ_S during BUW	Lower extremity joints (Deg)	FE angle	6.358 (0.882)	-1.317 (0.392)	< .001*
		AB/AD angle	2.929 (0.486)	-0.658 (0.234)	.006*
		RT angle	2.499 (0.201)	-0.317 (0.101)	.002*
	Trunk ($m/s\times10^{-2}$)	AP velocity	12.153 (1.716)	-2.431 (0.691)	< .001*
		ML velocity	7.255 (0.885)	-1.763 (0.383)	.092
		VT velocity	6.436 (1.150)	-1.647 (0.551)	.664

The models used was $\mathrm{MeanSD} = a + b \times \lambda_S$

* Significant relationship between local dynamic stability and gait variability ($p < .050$)

Figure Captions

Figure 1 — Illustration in all views of marker displacement

Figure 2 — Examples of a representative set of hip flexion-extension (FE) angle data. (a) Original time-series within 100 strides in 15570 seconds; (b) Normalized time-series within 100 strides into 10 thousands samples; (c) Normalized data embedded in a 3D state space (with time delay, i.e. τ of 10, and the real embedding dimension of 5), and (d) Average logarithmic divergence vs. stride. The best fit linear slope of the logarithmic relation from 0 to 0.5 stride represents λ_S.

Figure 3 — Examples of a set of hip flexion-extension (FE) angle data across the normalized stride duration. (a) Normalized time-series of 100 separate strides, and (b) Mean (solid line) ± SD (dash lines) for data shown in (a).

Figure 4 — The effects of the walking direction and slope grade on λ_S for the (a) FE, (b) AB/AD, and (c) RT motion of the lower extremity joints, and (a) AP, (b) ML, and (c) VT motion of the trunk (# indicates significant direction effect, while * indicates significant grade effect, $p < .050$, respectively)

Figure 5 — The effects of the walking direction and slope grade on MeanSD for the (a) FE, (b) AB/AD, and (c) RT motion of the lower extremity joints, and (a) AP, (b) ML, and (c) VT motion of the trunk (# indicates significant direction effect, while * indicates

significant grade effect, $p < .050$, respectively)

Appendix

Appendix Table The effects of the walking direction and slope grade on the total range of motion of the lower extremity joints, mean (SD)

		Total range of motion during FUW (deg)				Total range of motion during BUW (deg)			
		0%	**5%**	**10%**	**15%**	**0%**	**5%**	**10%**	**15%**
Hip	**FE Angle**	35.99 (6.26)	38.34 (5.83)[e]	40.07 (5.50)[a]	42.77 (5.03)[d]	30.37 (6.69)[#]	27.71 (6.03)[#,e]	23.82 (7.15)[#,a]	19.86 (6.50)[#,d]
	AB/AD Angle	8.07 (1.91)	8.38 (1.58)	8.36 (1.26)	8.09 (0.99)	5.87 (1.43)[#]	6.25 (1.75)[#]	6.75 (1.80)[#]	6.33 (1.60)[#]
	RT Angle	14.12 (3.30)	14.58 (3.165)	14.61 (3.06)	13.96 (2.95)	9.85 (3.14)[#]	9.26 (2.89)[#]	9.37 (2.46)[#]	8.55 (1.97)[#,d]
Knee	**FE Angle**	60.44 (9.78)	59.60 (8.72)	59.59 (9.04)	61.07 (9.47)	51.12 (11.61)[#]	51.51 (10.81)[#]	52.28 (11.20)[#]	53.03 (8.98)[#]
	AB/AD Angle	10.63 (4.04)	11.15 (3.93)	12.87 (4.20)[a]	13.02 (3.94)[b]	8.64 (3.53)[#]	8.18 (3.13)[#]	7.62 (3.16)[#]	7.96 (3.00)[#]
	RT Angle	15.22 (2.80)	14.34 (3.18)	13.79 (3.07)[c]	12.87 (2.89)[b]	13.05 (3.79)[#]	12.29 (3.61)[#]	11.97 (3.87)[c]	11.37 (3.87)[b]
Ankle	**FE Angle**	17.49 (4.09)	16.93 (5.01)	17.90 (5.52)	19.04 (6.03)	25.23 (4.39)[#]	28.01 (5.63)[#,e]	30.64 (5.41)[#,a]	32.12 (5.75)[#,d]
	AB/AD Angle	18.56 (3.18)	18.63 (3.71)	18.87 (4.04)	19.27 (4.24)	13.26 (2.77)[#]	13.00 (3.32)[#]	12.56 (3.23)[#]	12.44 (2.89)[#]
	RT Angle	10.41 (2.83)	10.67 (3.73)	10.64 (3.47)	10.30 (3.16)	10.45 (3.23)	10.69 (3.01)	11.61 (2.95)[a]	11.64 (2.75)[b]

[#] $p < .050$ for FUW compared to BUW within the grade condition

[a] $p < .010$ for 0%, 5% grade compared to 10% incline within the direction condition

[b] $p < .050$ for 0%, 5% grade compared to 15% incline within the direction condition

[c] $p < .050$ for 0% grade compared to 10% incline within the direction condition

[d] $p < .050$ for 0%, 5%, 10% grade compared to 15% incline within the direction condition

[e] $p < .050$ for 0% grade compared to 5% incline within the direction condition

[Insert **Appendix Figure**]

Appendix Figure — Scatterplots of λ_S against PWS for each of (a) the walking direction conditions, and (b) the slope grade conditions, for the trunk segment in anterior-posterior (AP) direction. Each symbol representing the λ_S of a particular participant. Lines with different dash types are the linear regression slopes for the particular condition.

Figures

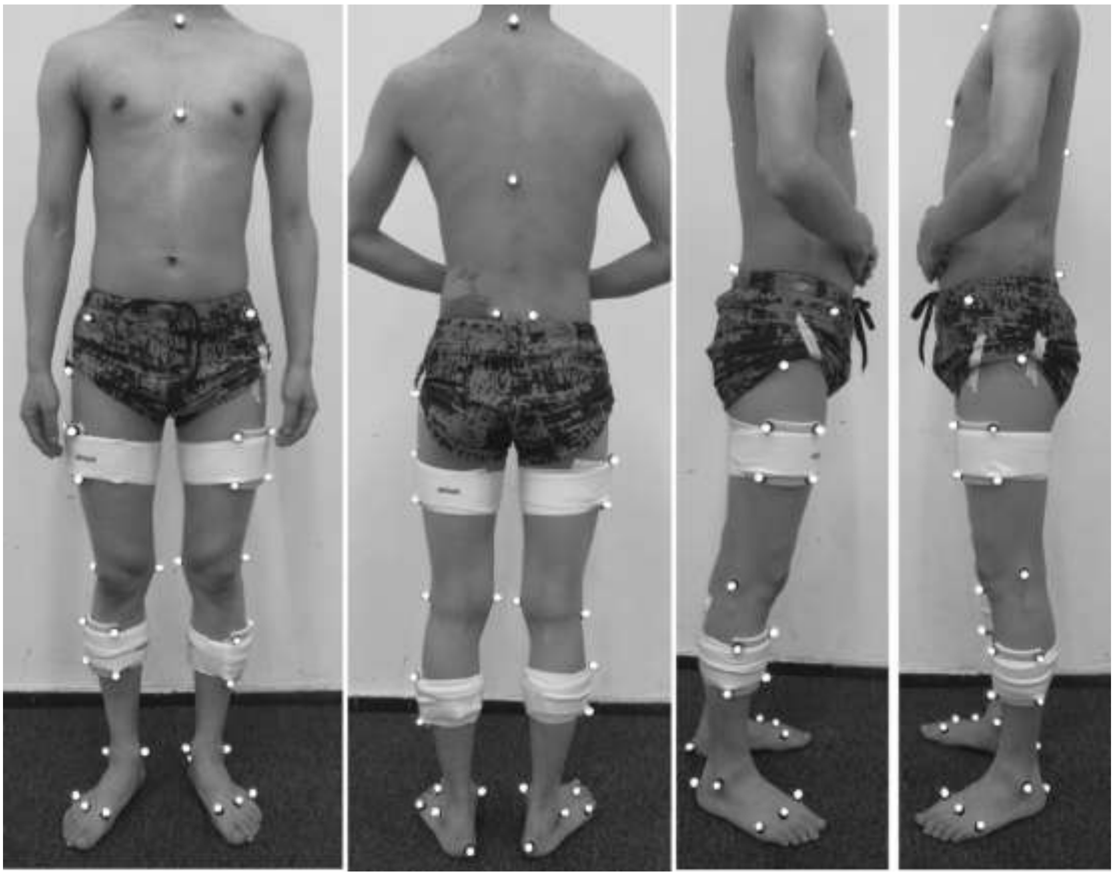


Figure 1

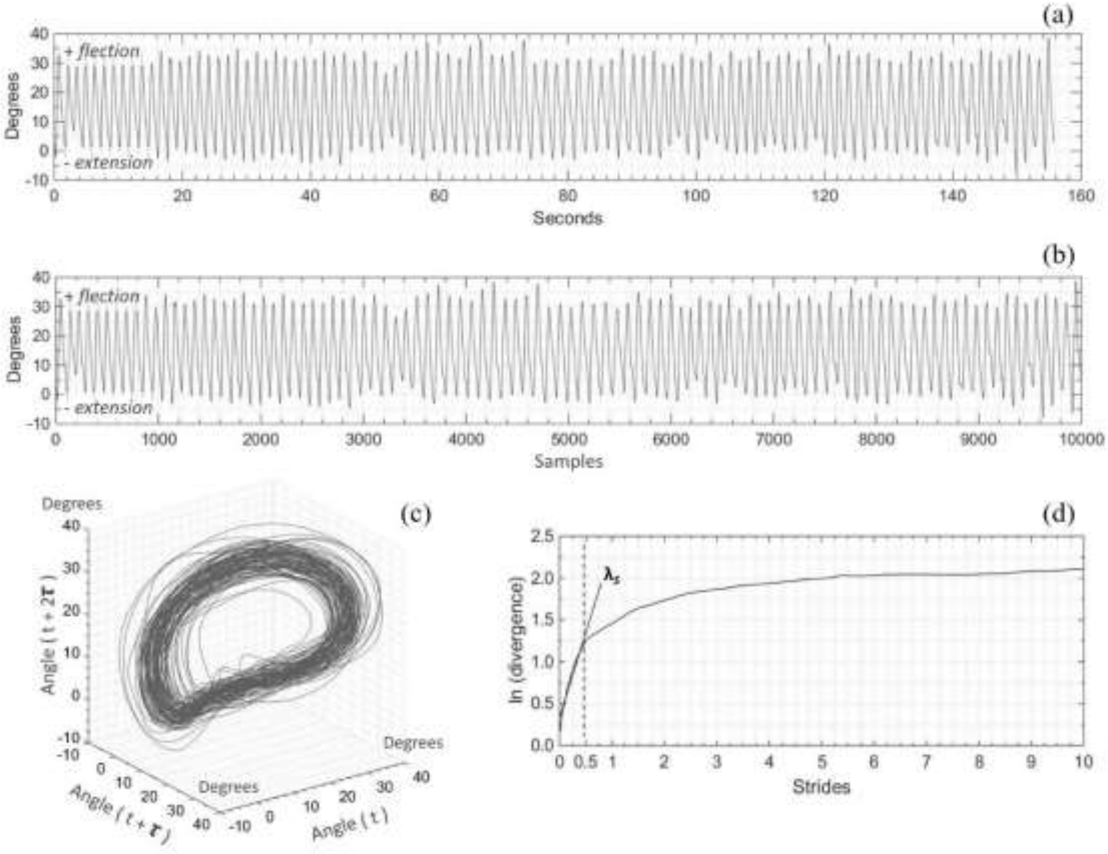

(a)
+ flection
- extension
Degrees
Seconds
(b)
+ flection
- extension
Degrees
Samples
(c)
Degrees
Angle (t + 2τ)
Angle (t + τ)
Angle (t)
(d)
λs
ln (divergence)
Strides

Figure 2

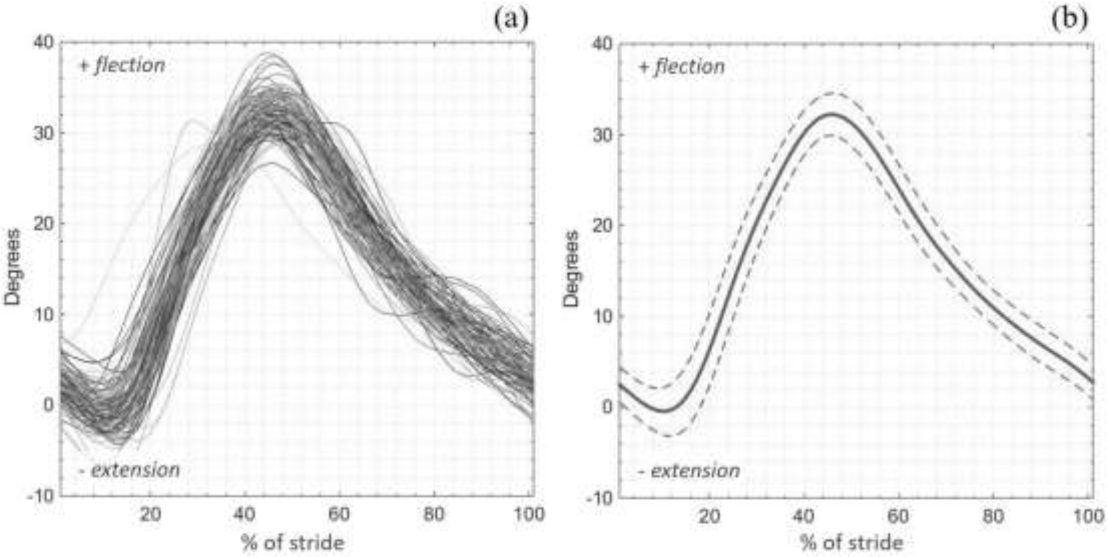
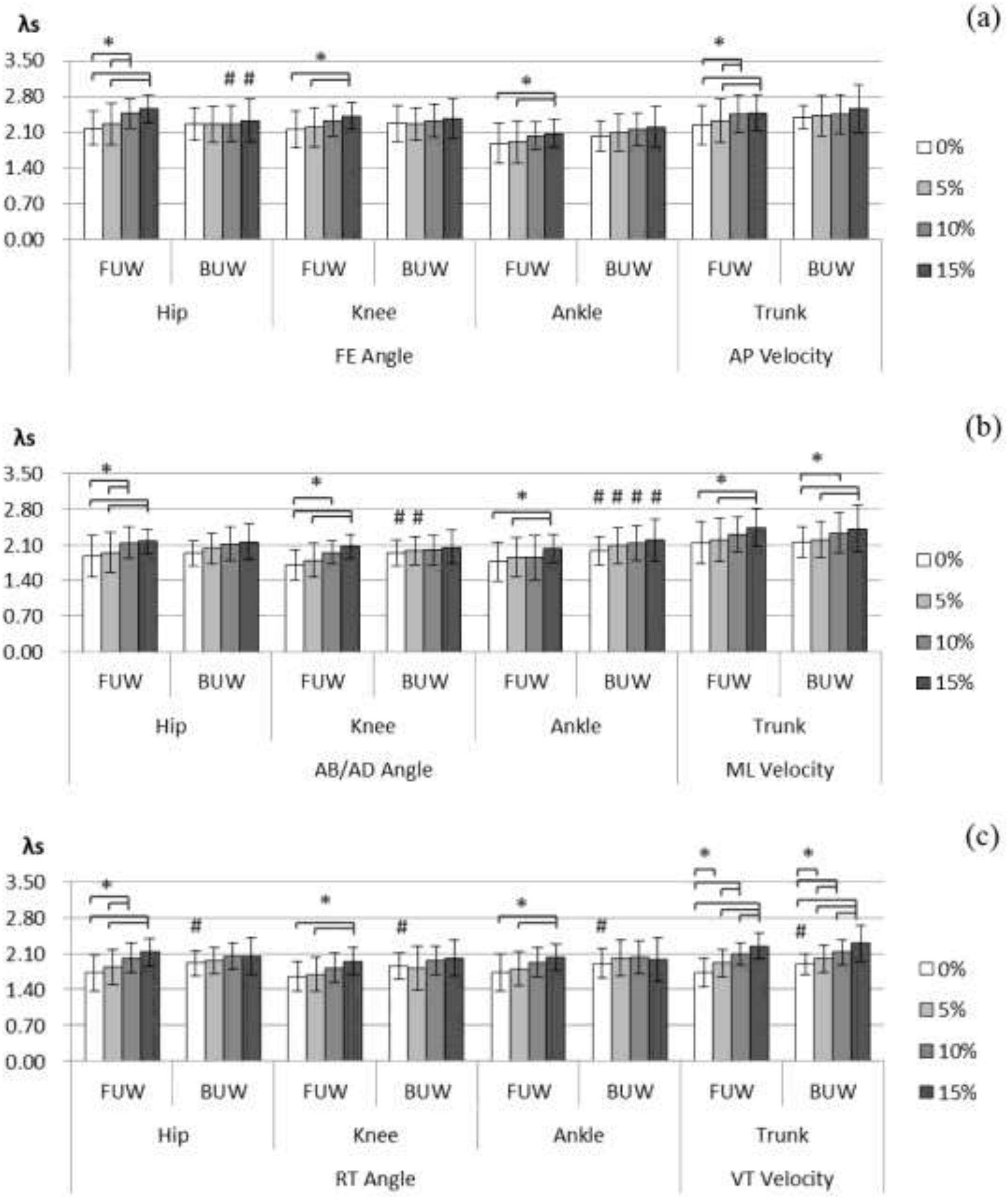

(a)
(b)
+ flection
- extension
Degrees
% of stride
40
30
20
10
0
-10
20
40
60
80
100

Figure 3


(a)
λs
3.50
2.80
2.10
1.40
0.70
0.00
*
# #
*
*
*
FUW
BUW
FUW
BUW
FUW
BUW
FUW
BUW
Hip
Knee
Ankle
Trunk
FE Angle
AP Velocity
□0%
▨5%
▨10%
■15%
(b)
λs
3.50
2.80
2.10
1.40
0.70
0.00
*
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FUW
BUW
FUW
BUW
FUW
BUW
FUW
BUW
Hip
Knee
Ankle
Trunk
AB/AD Angle
ML Velocity
□0%
▨5%
▨10%
■15%
(c)
λs
3.50
2.80
2.10
1.40
0.70
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FUW
BUW
FUW
BUW
FUW
BUW
FUW
BUW
Hip
Knee
Ankle
Trunk
RT Angle
VT Velocity
□0%
▨5%
▨10%
■15%

Figure 4

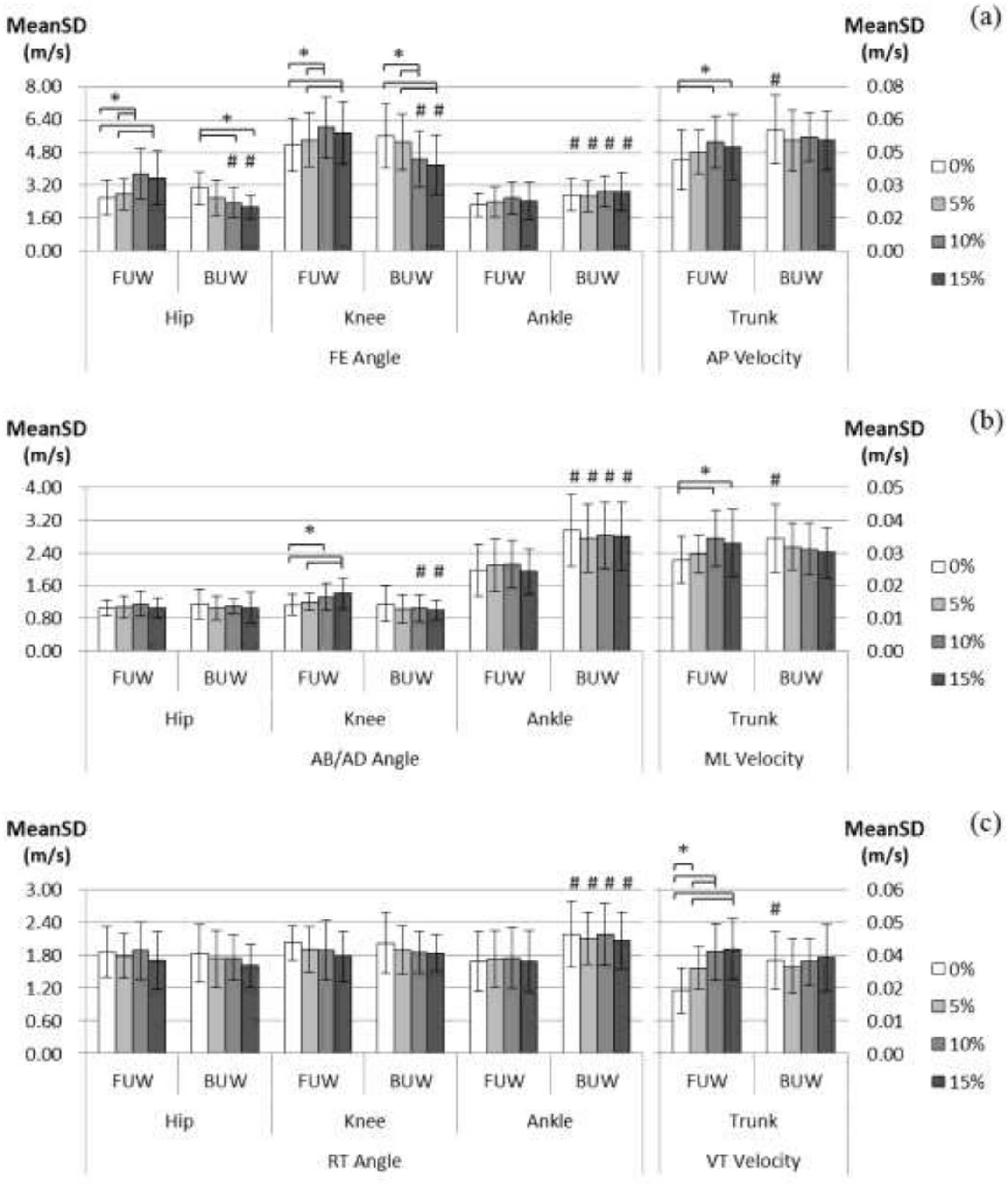
(a)
MeanSD (m/s)
8.00
6.40
4.80
3.20
1.60
0.00
MeanSD (m/s)
0.08
0.06
0.05
0.03
0.02
0.00
*
# #
# # # #
#
FUW
BUW
Hip
Knee
Ankle
Trunk
FE Angle
AP Velocity
□0%
▨5%
▨10%
■15%
(b)
MeanSD (m/s)
4.00
3.20
2.40
1.60
0.80
0.00
MeanSD (m/s)
0.05
0.04
0.03
0.02
0.01
0.00
AB/AD Angle
ML Velocity
(c)
MeanSD (m/s)
3.00
2.40
1.80
1.20
0.60
0.00
MeanSD (m/s)
0.06
0.05
0.04
0.02
0.01
0.00
RT Angle
VT Velocity

Figure 5

Appendix Figure