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Abstract

Typical healthy walking displays greater variability in the mediolateral direction compared to the anteroposterior direction. This greater variability is thought to represent increased uncertainty in movement. As a result, it has been postulated that the mediolateral direction of gait requires more active control by the central nervous system while the anteroposterior direction is controlled through passive actions. However, this theory has only been tested on gait where progression occurs in the anteroposterior direction. Therefore, the purpose of this study was to investigate how the amount of variability is affected if progression occurs in the mediolateral direction using a lateral stepping gait. Results showed the anteroposterior direction had a significantly greater amount of variability than the mediolateral direction ($p<0.001$). The results do not support current models of a partition of active control to different anatomical planes. Rather, it seems that other physical entities involved in motion, such as momentum and inertia, are able to decrease the dependence on active control from the central nervous system. In a lateral stepping gait, such physical entities were no longer assisting in the anteroposterior direction but had a larger impact in the mediolateral direction as it was the direction of progression. As a result variability in the anteroposterior direction increased. Thus, it is possible to infer increased reliance on active control from the central nervous system in the direction orthogonal to progression.

Keywords: gait, locomotion, motor control, variability, lateral stability

INTRODUCTION

Bipedal walking is a common task used as the primary means of human locomotion. Various theories have described different control mechanisms for maintaining a stable, cost effective gait. Based on modeling using passive dynamic walkers, forward progression of walking is maintained through an economical energy transfer between two pendulums, an inverted pendulum rotating about the stance leg and the pendulum motion of the swing leg (Kuo, 2007). The motion is primarily passive, requiring little active neural control. Robots have successfully been used to emulate this passive motion without any active control mechanism (Collins et al., 2005; Kuo, 2001; Kurz et al., 2008; McGeer, 1993). Robots can descend the gentle slope using only the pendulum dynamics and the added potential energy from gravity (Bauby and Kuo, 2000; Kurz and Stergiou, 2005; Kurz and Stergiou, 2007; Kurz et al., 2008). These passive walking robots necessarily have a wide base of support through either a wide "hip" piece or wide "feet". This added mechanical stability is to control the inherent mediolateral (ML) instability (Bauby and Kuo, 2000).

The human body however does not have excessively wide feet nor does healthy gait use a wide base of support. Yet humans are stable enough in the ML direction to maintain an upright position. This is likely the result of the central nervous system using sensory integration feedback from visual, vestibular, and proprioceptive systems to control lateral foot placement to constantly maintain an upright, stable gait (Dean et al., 2007; O'Connor and Kuo, 2009). Theoretically, the anteroposterior (AP) direction is stable from passive dynamics; ML direction stability is maintained actively by higher brain centers (O'Connor and Kuo, 2009). In the context of this manuscript, active processes will refer to supraspinal mechanisms whereas all others (e.g. spinal reflexes, mechanical constraints, etc.) will be collectively grouped as passive. Theoretical

presentation of active control of lateral balance has been supported through studies comparing the amount of variability in the ML direction to the AP direction during walking (Bauby and Kuo, 2000; Dean et al., 2007; O'Connor and Kuo, 2009).

The amount of variability in gait has proven to be closely linked to the ability to maintain upright stability (Brach et al., 2005; Brach et al., 2007; Maki, 1997). In one prospective study, variability in the speed of gait between strides was shown to be the best predictor of falling in an elderly population (Maki, 1997). Similarly, a more recent study found that an increase in the amount of stance time variability was associated with higher incidence of mobility disability in the elderly (Brach et al., 2007). In addition, Brach et al (Brach et al., 2005) found step width variability to be associated with falls in elderly individuals. It has been suggested that the increased amount of variability is associated with decreased motor control in the elderly (Buzzi et al., 2003). Thus, an appreciation of variability gives a strong foundation for understanding the upright stability of an individual during locomotion. Furthermore, it is possible to examine the amount of variability in gait to infer active control (Bauby and Kuo, 2000). In addition, the impact of active control of the ML direction is demonstrated when a combined impairment of vision and the vestibular system results in a large amount of ML variability despite intact proprioception; an effect that was not as drastic however in the AP direction (O'Connor and Kuo, 2009).

Despite the building evidence that AP movement is passive and ML involves greater active function (Bauby and Kuo, 2000; Dean et al., 2007; O'Connor and Kuo, 2009), there is a knowledge gap in the literature. All previous studies have aligned the direction of progression with the AP direction. This is an expected bias since humans' primary direction of progression when walking is the AP direction. This presents the problem that physical properties associated

with motion, such as inertia and momentum, would significantly contribute to the AP directional movement with a lesser impact on the ML direction. However, if AP directional control is passive and ML directional control is dependent more on the central nervous system, then a change in the direction of progression should not affect the amount of variability in the AP or ML directions. More specifically, the ML direction should still present a greater amount of variability than the AP direction.

Therefore, the purpose of this study was to investigate how the amount of variability is affected if progression occurs in the ML direction using a lateral stepping gait. Based on current literature proposing active lateral control for stabilization (Bauby and Kuo, 2000), it was hypothesized that the ML direction would still exhibit a greater amount of variability than the AP direction.

METHODS

Subjects

Twenty subjects were recruited for participation to perform a lateral stepping gait (Table 1; Figure 1). Of these twenty, a subpopulation of six individuals returned within 9 months for a second visit to perform a typical AP progression gait to allow for inferential comparison. All participants gave written, informed consent in accordance with our Medical Center's Institutional Review Board. Inclusion criteria included cognitive ability to give written informed consent and currently exercising 2-3 times a week. Exclusion criteria included inability to give written consent, pregnancy, as well as any neurological, vestibular, or musculoskeletal conditions that would affect the participant's typical gait.

INSERT FIGURE 1 AND TABLE 1 ABOUT HERE

Study Protocol

A one-shot repeated measures design was utilized for this study. All data collections occurred at the Nebraska Biomechanics Core Facility. Subjects wore their own standard athletic shoes. Retroreflective markers were affixed to the posterior heel and top of the second metatarsophalangeal joint on both legs of each subject. Subjects were instructed to perform a lateral stepping gait on a treadmill at their preferred speed. An eight camera motion capture system tracked the marker position in real time at 60 Hz (EvaRT, Motion Analysis, Santa Rosa, CA, USA). A low-pass fourth-order Butterworth filter with a 5 Hz cut-off frequency was used to smooth marker trajectories. Individuals performed a trial facing to the left and a trial facing the right, this permitted the right and left leg to be in either a lead leg or lag leg position for one trial. Data for trials with the right leg lagging and for the left leg lagging were not combined for analysis. Subjects were given the following specific instructions on how to perform the lateral stepping gait: 1) keep head up while stepping laterally, 2) do not allow feet to cross at any point, 3) feet and legs are to point in the same direction as the body and not turned toward the direction of progression, and 4) at no point should both feet be off the walkway (i.e. no flight phase as found in a run or skip gait).

Preferred speed was determined by having the subject start the lateral stepping at the slowest speed possible by the treadmill. Speed was then incrementally increased by 0.045 m/s until the subject verbally communicated that preferred speed had been reached. Preferred speed was confirmed by then increasing the treadmill speed by an additional 0.045 m/s to confirm that the speed had at that point surpassed the preferred speed. Following selection of preferred speed, subjects were given a one minute rest period, after which they then completed a three minute practice trial for each direction in order to familiarize themselves with the lateral stepping gait.

After the completion of the practice trial, subjects performed the data trials consisting of three minutes of continuous lateral stepping gait. Data for each subject's trials were then exported for analysis.

In addition, a subpopulation of six of the twenty individuals returned on a separate day to complete a typical AP progression walking trial. Subjects walked for 3 minutes on a treadmill at their preferred AP progression walking speed determined in the same manner as above. Marker trajectories for the AP progression walking trials were captured at the same sampling rate (60 Hz) as the lateral stepping trials and were smoothed similarly.

Data Analysis

Foot position was denoted as the midpoint of the heel and metatarsophalangeal joint markers during stance (O'Connor et al., 2007). Step width and length were then calculated as the Euclidean distance in the ML and AP directions, respectively, between the leading and lagging foot following each successive step (Figure 2). The lateral stepping gait requires different tasks from the leading leg and the lagging leg. As a result, the step width and length for the leading and lagging leg were measured separately. This meant that the lagging step width (Lag ML) and lagging step length (Lag AP) were the distances in the ML and AP directions following movement of the lag leg closer to the lead leg. The lead step width (Lead ML) and lead step length (Lead AP) were then the distances in the ML and AP directions following the movement of the lead leg away from the lag leg (Figure 2). For all trials, the first 100 steps of both the lead and lag legs were included for analysis. Standard deviation of each step was found and then normalized by its mean distance to yield the coefficient of variation (CoV) for the Lag ML, Lead ML, Lag AP, and Lead AP. Trials for right leg lagging and left leg lagging were analyzed separately.

INSERT FIGURE 2 ABOUT HERE

For the AP progression walking trials, foot position was calculated in the same manner, as the midpoint between the heel and toe markers. Since AP progression walking is reciprocal and all subjects were healthy, young individuals without any atypical symmetry between legs, right and left steps were not separated for calculations of step width and length. Step width and length were calculated as the Euclidean distance in the ML and AP directions from one foot center to the other when the foot had stopped forward progression (O'Connor et al., 2007). The AP direction also included the movement of the treadmill belt (O'Connor and Kuo, 2009). This was the same manner as was utilized for the lateral stepping trials. Similar to the lateral stepping trials, the first 100 steps were included for analysis. Standard deviation of step length and width was found and normalized by the mean distance for each to yield the CoV. All measurements and calculations were performed using custom Matlab software (Matlab 2010, Mathworks Inc., Concord, MA, USA).

Differences in absolute variability (standard deviation) and normalized variability (CoV) for Lag ML, Lead ML, Lag AP, and Lead AP were tested through a 2x2 (plane by leg) fully repeated analysis of variance with significance noted at the alpha equal to 0.05 level for the right leg lagging and left leg lagging trials separately.

RESULTS

Anteroposterior Progression Gait

For the anteroposterior (AP) progression gait, the average preferred speed for the subpopulation was 1.013 ± 0.166 m/s (range 0.760 - 1.207 m/s). For the six individuals that returned to perform a typical AP progression walking trial, the ML direction had an average

length of 144.27 ± 11.56 mm, standard deviation of 18.23 ± 5.90 mm, and CoV of 0.13 ± 0.04. The AP direction had an average length of 576.08 ± 49.74 mm, standard deviation of 19.69 ± 6.45 mm, and CoV of 0.03 ± 0.01 for the group.

Lateral Stepping Gait

For the mediolateral (ML) progression gait (i.e. lateral stepping gait), the average preferred speed for all subjects was 0.333 ± 0.042 m/s (range 0.268 - 0.402 m/s).

Absolute Variability (Standard Deviation)

The standard deviation for the ML direction was significantly greater than the AP direction for the trials with right leg lagging ($F_{1,19}$=57.841, p<0.001; Table 2 & 3) and left leg lagging ($F_{1,19}$=86.868, p<0.001; Table 4 & 5). The standard deviation for the leading leg was significantly greater than the lagging leg for right leg lagging trials ($F_{1,19}$=87.263, p<0.001) and for left leg lagging trials ($F_{1,19}$=28.856, p<0.001). There was a significant interaction for both right leg lagging trials ($F_{1,19}$=61.010, p<0.001) and for left leg lagging trials ($F_{1,19}$=33.947, p<0.001).

Normalized Variability (Coefficient of Variation)

The CoV for the AP direction was significantly greater than the ML direction for the trials with right leg lagging ($F_{1,19}$=920.462, p<0.001; Table 2 & 3) and left leg lagging ($F_{1,19}$=738.662, p<0.001; Table 4 & 5). There was no difference in CoV for the leading leg versus lagging leg for right leg lagging trials ($F_{1,19}$=0.148, p=0.705) or for left leg lagging trials ($F_{1,19}$=0.073, p=0.790). There was no significant interaction for either right leg lagging trials ($F_{1,19}$=4.316, p=0.052) or for left leg lagging trials ($F_{1,19}$=3.848, p=0.065).

INSERT TABLES 2, 3, 4, and 5 ABOUT HERE

DISCUSSION

Absolute versus Normalized Variability

We initially set out to determine the amount of variability present in the AP and ML directions during a novel gait task that aligned the progression with the ML as opposed to the typical AP direction. This would permit better understanding of whether the directional control of gait is a "hard-wired" partition within the motor control system, or whether in fact it is dynamical, adjusting the active control depending on the direction of the gait. It was not clear as to whether an absolute measure of variability (i.e. standard deviation) or a normalized measure (i.e. CoV) would be more appropriate and as such both were examined. Our overall purpose though was to compare the variability in the AP versus ML direction of gait.

The results for the normalized measure of variability (i.e. CoV) showed that during the lateral stepping gait, the AP direction had significantly greater variability than the ML direction. This persisted despite the gross differences in the average magnitudes of the movements for AP direction versus ML direction as well as the magnitude differences for the lead step and lag step in the ML direction, confirmed by the lack of a significant interaction. When comparing standard deviation, the ML direction values were greater than the AP direction, but closer inspection of the group means (Tables 2 and 4) showed that the ML direction had greater values because of the standard deviation in the lead step in particular. The lag step in the ML direction, however, is similar to the lag step and lead step of the AP direction. This was confirmed by the significant interactions. From the standard deviations, then it is possible to conclude 1 of 2 things: 1) there is no difference in AP and ML control, or 2) the utilization of absolute variability to compare

human movements of grossly different magnitudes (average lengths in Tables 2 and 4) is inappropriate.

Anteroposterior versus Mediolateral Control

Based on the variability analyses, comparing AP and ML direction variability in a novel gait task, it can only be concluded that the results did not support our hypothesis. Interpretation of the absolute variability could lead to the conclusion of no distinct control differences between directions. However, inconsistency between lag and lead step standard deviations in the AP direction does not offer any insight into directional control, but rather highlights the dependency of standard deviation on means. Thus, we consider the normalized variability, which portrays a more detailed picture of the control differences for AP and ML direction. Specifically, the change in the direction of progression of gait resulted in a greater amount of variability in the AP direction than the ML direction. Closer inspection of the subpopulation's forward walking trials leads to the interpretation that there is no difference in directional control (standard deviation) or greater ML control with increased variability (CoV); this is exactly opposite to the lateral stepping results. It seems without physical entities such as inertia and momentum assisting the AP direction, the amount of variability for foot placement becomes larger in the AP direction than the ML direction. It was not expected to see a difference in CoV of such magnitude between the two planes. The magnitude of difference for AP compared to ML direction in the lateral stepping gait was much greater and in opposite direction to the step CoV values for our subpopulation that performed a typical AP progression walk (group mean AP: 0.03 ± 0.01, ML: 0.13 ± 0.04). Brach et al (Brach et al., 2005) reported CoV measures for elderly non-fallers in typical AP progression walking comparable to our subpopulation (group mean AP: 0.075 ±

0.034, ML: 0.156 ± 0.159). The large magnitudes of the CoV measures found for the lateral stepping gait may be the result of the novelty of the task.

These findings produce interesting comparisons with what has previously been reported in studies comparing variability in the AP and ML directions (Bauby and Kuo, 2000; O'Connor and Kuo, 2009). Bauby & Kuo (2000) reported greater variability in the ML direction while O'Connor & Kuo (2009) had similar findings while subjecting individuals to visual perturbations during typical AP gait. Their results led to a conclusion of increased active neural control of the ML direction (O'Connor and Kuo, 2009). However, in both of these studies, the direction of progression for their subjects was in the AP direction. In a lateral stepping gait, the AP had greater normalized variability than the ML. Yet, similar to these previous studies, the direction aligned with the progression had less normalized variability than the secondary direction orthogonal to the line of progression.

The lateral stepping gait orients the body in such a manner that physical entities associated with motion such as momentum and inertia are possibly having a larger impact on the ML direction but at the least are not influencing the AP direction to the same degree as is the case in forward walking. Our results showed that the AP direction had a greater amount of variability than the ML direction when it was no longer strongly influenced by these entities. This indicates that physical entities associated with motion such as momentum and inertia can seemingly offload the active control from the central nervous system. This is particularly important in consideration of elderly walkers. Specifically, the elderly have shown greater amounts of variability in their steps than the young (Owings and Grabiner, 2004b). Elderly walkers also typically walk at slower velocities. While a slower walking velocity has been considered a compensatory mechanism to increase upright stability and not fall over, a slower

velocity would also decrease the effects of physical entities associated with motion such as momentum and inertia. Such decreased effects from these entities could be causing increased active control from the central nervous system. Thus, by consuming increased cognitive load, the slowed velocity may be perpetuating decreased upright stability in the elderly during gait. However, this does not imply simply increasing speed will increase upright stability as any potential mechanisms that are causing slowed velocity in individuals should be considered as these factors may produce a greater decrease in upright stability than would be gained by contributions from physical entities associated with motion.

Study Limitations

Our results should be viewed in lieu of the following limitations. First, contrary to Bauby and Kuo (2000), subjects were ambulating on a treadmill. As a result, the space constraints of the treadmill as well as the motion of the treadmill belt may have influenced the measures. However, other groups have previously concluded that treadmill gait results in similar variability magnitudes as overground gait (Owings and Grabiner, 2004a), leading us to believe that the directional results of our study would not be affected. Second, our study utilized variability to infer active control similar to previous literature (Bauby and Kuo, 2000; O'Connor and Kuo, 2009). Future work should improve upon these findings by measuring active control through other means. Third, our study aimed to compare the AP and ML variability during a lateral stepping gait. Comparing the magnitudes of variability in the lateral stepping gait to a typical AP progression gait is difficult due to lack of training in the lateral stepping gait. Future work should attempt to address the novelty of the lateral stepping gait through possible training programs. Finally, the preferred speed for the lateral stepping gait was considerably less than the one found in typical AP progression walking. This was done, however, to permit individuals to walk at their

comfortable speed. Forcing the lateral stepping gait to a faster speed, or doing a similar study with forcing subjects to walk slower in an AP progression gait would result in non-optimized dynamics and lead to altered variability.

CONCLUSION

In summary, the control of the directions of movement do not seem to be set but rather it appears that the amount of active control in any direction is dependent on the direction of progression. Increased active control is assumed over the direction least benefiting from the impact of passive physical entities associated with motion such as momentum and inertia. The direction that is orthogonal to the progression will have the least amount of influence from these entities (e.g. inertia and momentum) and thus we expect it to have greater dependence upon active neural control for foot placement. Further work should attempt to evoke changes in the amount of variability in the AP and ML plane, thereby allowing for analysis of which direction is more sensitive to perturbation.

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Conflict of interest statement

None of the authors have any conflict of interest.

Abbreviations

ML - mediolateral

AP - anteroposterior

Hz - Hertz

m - meter

s - second

CoV - coefficient of variation

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Table 1: Subject Demographics.

Gender	15 M, 5 F
Age (years)	23.05 ± 3.05
Preferred Speed (m/s)	0.333 ± 0.042
(Range: Minimum - Maximum)	0.268 - 0.402
Height (cm)	177.23 ± 9.37
Mass (kg)	78.46 ± 18.11
Leg Dominance	19 R, 1 L

Table 2: Average step lengths, standard deviations, and coefficient of variation for right leg lagging trials for group (n=20).
Group means ± standard deviation

	Anteroposterior (AP)		*Mediolateral (ML)*	
	Lag Step	*Lead Step*	*Lag Step*	*Lead Step*
Average (mm)	22.44 ± 11.18	24.62 ± 12.60	152.01 ± 34.95	597.01 ± 85.10
Standard Deviation (mm)	14.02 ± 5.33	16.08 ± 4.81	17.71 ± 6.54	32.55 ± 7.34
Coefficient of Variation	0.66 ± 0.13	0.71 ± 0.15	0.12 ± 0.03	0.05 ± 0.01

Table 3: Mean, standard deviation (SD), coefficient of variation (CoV) for the step width and length measures during right leg lagging trials.

		Anteroposterior (AP)		*Mediolateral (ML)*				*Anteroposterior (AP)*		*Mediolateral (ML)*	
Subject		*Lag Step*	*Lead Step*	*Lag Step*	*Lead Step*	*Subject*		*Lag Step*	*Lead Step*	*Lag Step*	*Lead Step*
1†	Mean (mm)	17.21	32.01	154.65	668.52	11	Mean (mm)	20.99	25.43	147.17	554.05
	SD (mm)	13.65	20.75	15.63	31.45		SD (mm)	17.21	16.47	17.42	35.49
	CoV	**0.79**	**0.65**	**0.10**	**0.05**		**CoV**	**0.82**	**0.65**	**0.12**	**0.06**
2†	Mean (mm)	10.28	11.48	110.93	442.58	12†	Mean (mm)	25.77	19.70	225.84	691.08
	SD (mm)	7.35	9.45	10.83	20.06		SD (mm)	13.77	17.37	24.44	41.68
	CoV	**0.71**	**0.82**	**0.10**	**0.05**		**CoV**	**0.53**	**0.88**	**0.11**	**0.06**
3	Mean (mm)	13.26	15.42	124.58	454.56	13	Mean (mm)	13.30	19.34	127.62	607.79
	SD (mm)	9.92	11.66	11.77	31.09		SD (mm)	10.19	11.78	14.55	25.75
	CoV	**0.75**	**0.76**	**0.09**	**0.07**		**CoV**	**0.77**	**0.61**	**0.11**	**0.04**
4	Mean (mm)	17.50	15.53	214.68	625.39	14	Mean (mm)	20.00	17.56	140.88	607.68
	SD (mm)	14.27	12.43	33.02	45.88		SD (mm)	14.94	12.68	13.28	25.73
	CoV	**0.82**	**0.80**	**0.15**	**0.07**		**CoV**	**0.75**	**0.72**	**0.09**	**0.04**
5	Mean (mm)	9.65	12.82	160.83	569.01	15	Mean (mm)	13.06	16.83	141.03	598.24
	SD (mm)	6.19	9.98	13.97	22.18		SD (mm)	10.48	11.19	10.95	27.62
	CoV	**0.64**	**0.78**	**0.09**	**0.04**		**CoV**	**0.80**	**0.66**	**0.08**	**0.05**
6†	Mean (mm)	25.69	26.67	128.26	690.58	16	Mean (mm)	52.39	30.93	129.09	525.20
	SD (mm)	15.79	24.65	18.90	40.75		SD (mm)	30.49	18.69	14.63	33.09
	CoV	**0.61**	**0.92**	**0.15**	**0.06**		**CoV**	**0.58**	**0.60**	**0.11**	**0.06**
7†	Mean (mm)	41.92	63.95	144.58	685.68	17	Mean (mm)	17.90	22.65	115.20	437.43
	SD (mm)	19.89	24.06	13.27	43.27		SD (mm)	12.56	16.43	7.97	26.36
	CoV	**0.47**	**0.38**	**0.09**	**0.06**		**CoV**	**0.70**	**0.73**	**0.07**	**0.06**
8	Mean (mm)	35.79	21.20	126.40	620.91	18	Mean (mm)	24.45	28.85	206.75	706.64
	SD (mm)	18.36	20.05	28.82	27.27		SD (mm)	16.41	19.45	26.12	42.17
	CoV	**0.51**	**0.95**	**0.23**	**0.04**		**CoV**	**0.67**	**0.67**	**0.13**	**0.06**
9	Mean (mm)	35.37	19.98	124.26	646.25	19	Mean (mm)	14.18	43.29	148.91	607.77
	SD (mm)	14.98	14.43	17.60	28.45		SD (mm)	10.20	19.54	17.14	32.93
	CoV	**0.42**	**0.72**	**0.14**	**0.04**		**CoV**	**0.72**	**0.45**	**0.12**	**0.05**
10†	Mean (mm)	19.55	11.64	210.96	682.39	20	Mean (mm)	20.55	37.18	157.50	518.46
	SD (mm)	8.92	9.79	21.59	34.83		SD (mm)	14.90	20.81	22.36	34.99
	CoV	**0.46**	**0.84**	**0.10**	**0.05**		**CoV**	**0.72**	**0.56**	**0.14**	**0.07**

The anteroposterior (AP) direction had significantly more variability than the mediolateral (ML), reflecting greater uncertainty in foot placement and inferring increased active neural control in the AP direction.

(Bold) Sig. $p<0.05$ AP vs. ML

† Returned for AP progression walking trial

Table 4: Average step lengths, standard deviations, and coefficient of variation for left leg lagging trials for group (n=20).
Group means ± standard deviation

	Anteroposterior (AP)		*Mediolateral (ML)*	
	Lag Step	*Lead Step*	*Lag Step*	*Lead Step*
Average (mm)	22.53 ± 12.55	22.05 ± 10.14	151.18 ± 38.21	593.20 ± 76.21
Standard Deviation (mm)	13.50 ± 4.07	14.62 ± 3.99	15.82 ± 6.53	30.18 ± 5.15
Coefficient of Variation	0.67 ± 0.15	0.71 ± 0.12	0.10 ± 0.03	0.05 ± 0.01

Table 5: Mean, standard deviation (SD), coefficient of variation (CoV) for the step width and length measures during left leg trials.

		Anteroposterior (AP)		*Mediolateral (ML)*				*Anteroposterior (AP)*		*Mediolateral (ML)*	
Subject		*Lag Step*	*Lead Step*	*Lag Step*	*Lead Step*	*Subject*		*Lag Step*	*Lead Step*	*Lag Step*	*Lead Step*
1†	Mean (mm)	22.18	19.14	144.70	619.67	11	Mean (mm)	13.89	17.94	153.49	607.13
	SD (mm)	14.78	15.17	21.76	25.50		SD (mm)	11.83	13.87	15.03	34.85
	CoV	**0.67**	**0.79**	**0.15**	**0.04**		**CoV**	**0.85**	**0.77**	**0.10**	**0.06**
2†	Mean (mm)	16.84	13.09	124.66	453.55	12†	Mean (mm)	22.66	17.97	174.28	610.84
	SD (mm)	10.83	9.33	16.35	28.45		SD (mm)	14.29	13.65	11.69	29.57
	CoV	**0.64**	**0.71**	**0.13**	**0.06**		**CoV**	**0.63**	**0.76**	**0.07**	**0.05**
3	Mean (mm)	20.34	14.61	125.07	477.04	13	Mean (mm)	23.68	46.11	116.22	585.48
	SD (mm)	13.09	10.11	9.80	27.68		SD (mm)	12.66	18.45	10.51	31.54
	CoV	**0.64**	**0.69**	**0.08**	**0.06**		**CoV**	**0.53**	**0.40**	**0.09**	**0.05**
4	Mean (mm)	21.54	34.97	199.01	585.16	14	Mean (mm)	16.63	26.41	134.18	604.27
	SD (mm)	19.51	18.87	18.53	24.96		SD (mm)	13.70	16.57	10.19	29.98
	CoV	**0.91**	**0.54**	**0.09**	**0.04**		**CoV**	**0.82**	**0.63**	**0.08**	**0.05**
5	Mean (mm)	8.34	12.25	181.66	591.86	15	Mean (mm)	9.92	15.67	134.04	635.85
	SD (mm)	6.11	9.50	14.83	21.05		SD (mm)	7.80	11.30	11.91	20.40
	CoV	**0.73**	**0.78**	**0.08**	**0.04**		**CoV**	**0.79**	**0.72**	**0.09**	**0.03**
6†	Mean (mm)	44.44	18.96	107.46	700.86	16	Mean (mm)	60.66	46.55	134.85	489.27
	SD (mm)	17.42	16.85	16.52	37.07		SD (mm)	18.74	23.32	15.85	35.18
	CoV	**0.39**	**0.89**	**0.15**	**0.05**		**CoV**	**0.31**	**0.50**	**0.12**	**0.07**
7†	Mean (mm)	22.71	26.68	156.67	645.85	17	Mean (mm)	20.23	27.88	132.79	453.27
	SD (mm)	13.91	19.41	16.71	30.12		SD (mm)	15.83	19.68	14.87	35.05
	CoV	**0.61**	**0.73**	**0.11**	**0.05**		**CoV**	**0.78**	**0.71**	**0.11**	**0.08**
8	Mean (mm)	26.71	15.14	113.90	646.35	18	Mean (mm)	19.09	19.92	261.44	684.08
	SD (mm)	15.02	12.77	10.50	25.10		SD (mm)	13.02	14.65	38.08	31.30
	CoV	**0.56**	**0.84**	**0.09**	**0.04**		**CoV**	**0.68**	**0.74**	**0.15**	**0.05**
9	Mean (mm)	37.93	21.50	177.79	670.91	19	Mean (mm)	8.28	19.07	130.70	575.65
	SD (mm)	21.22	16.23	24.02	38.58		SD (mm)	7.20	12.00	10.76	32.95
	CoV	**0.56**	**0.75**	**0.14**	**0.06**		**CoV**	**0.87**	**0.63**	**0.08**	**0.06**
10†	Mean (mm)	14.13	12.02	201.37	687.89	20	Mean (mm)	20.37	15.08	119.32	539.02
	SD (mm)	8.35	9.96	16.92	28.03		SD (mm)	14.75	10.72	11.66	36.18
	CoV	**0.59**	**0.83**	**0.08**	**0.04**		**CoV**	**0.72**	**0.71**	**0.10**	**0.07**

The anteroposterior (AP) direction had significantly more variability than the mediolateral (ML), reflecting greater uncertainty placement and inferring increased active neural control in the AP direction.

(Bold) Sig. $p<0.05$ AP vs. ML

† Returned for AP progression walking trial

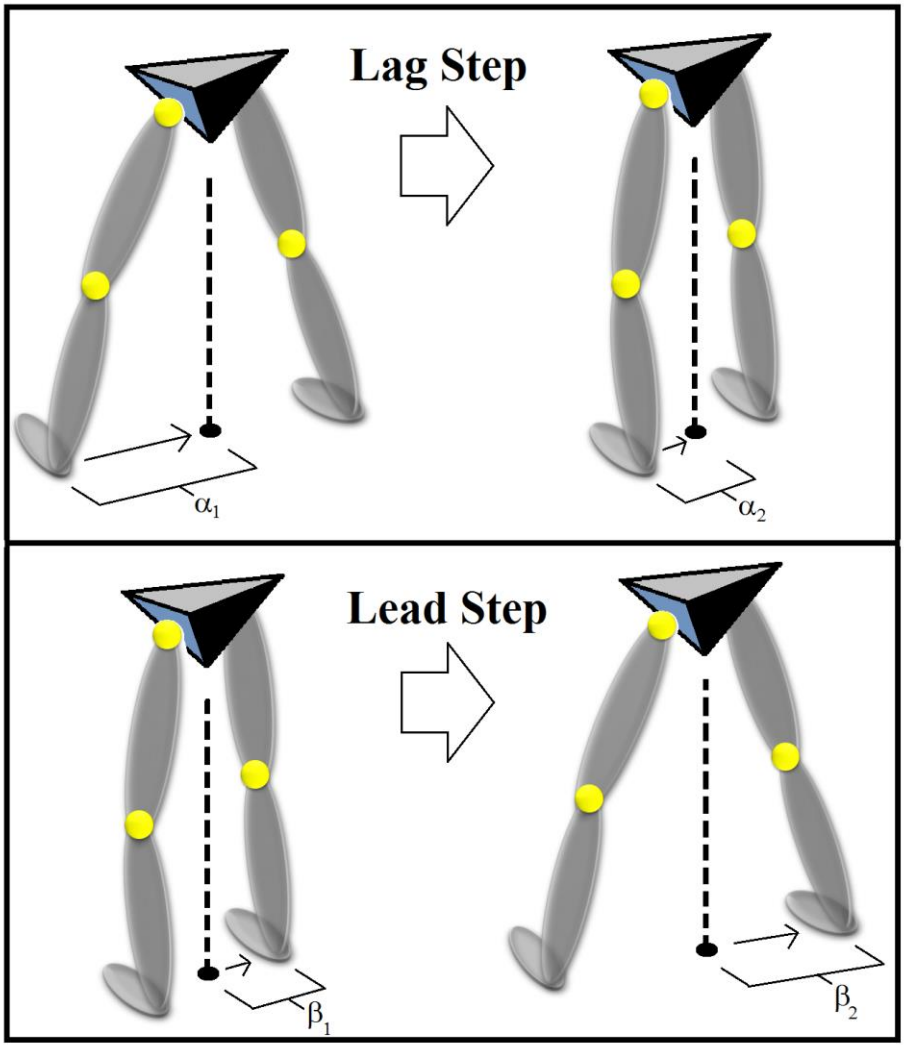

Figure 1: Lower limb diagram showing the lateral stepping gait for two different steps. (Top) The lag step shows the left leg stepping closer to the individual's center of mass (dropped down on dashed line)($\alpha_2 < \alpha_1$). (Bottom) The lead step has the right foot stepping away from the individual's center of mass (dropped down on dashed line) ($\beta_2 > \beta_1$).

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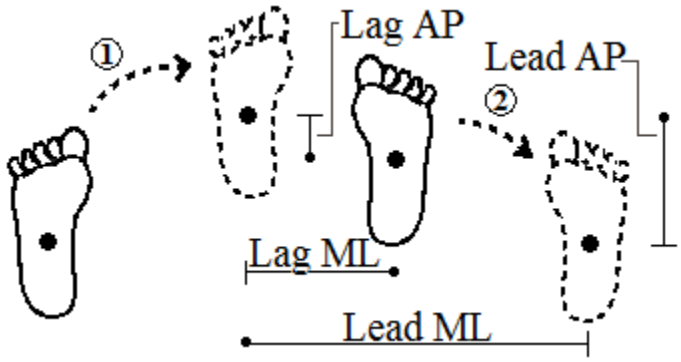

Figure 2: Lag and lead step measures in anteroposterior (AP) and mediolateral (ML) planes. The Lag AP and Lag ML are measured from the center of the leading foot's position to the center of the lagging foot's position following movement of the lagging leg. The Lead AP and Lead ML are measured from the center of the lagging foot's position to the center of the leading foot's position following movement of the leading leg. This shows a lag step first (1) followed by a lead step (2).