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1 **Variability of Gait is Dependent on Direction of Progression: Implications for Active**
2 **Control**

3

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15

16 Original Article

17 word count: 3,462

18

19

20 **Abstract**

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

38

39

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

41

42

43 INTRODUCTION

44 Bipedal walking is a common task used as the primary means of human locomotion.
45 Various theories have described different control mechanisms for maintaining a stable, cost
46 effective gait. Based on modeling using passive dynamic walkers, forward progression of
47 walking is maintained through an economical energy transfer between two pendulums, an
48 inverted pendulum rotating about the stance leg and the pendulum motion of the swing leg (Kuo,
49 2007). The motion is primarily passive, requiring little active neural control. Robots have
50 successfully been used to emulate this passive motion without any active control mechanism
51 (Collins et al., 2005; Kuo, 2001; Kurz et al., 2008; McGeer, 1993). Robots can descend the
52 gentle slope using only the pendulum dynamics and the added potential energy from gravity
53 (Bauby and Kuo, 2000; Kurz and Stergiou, 2005; Kurz and Stergiou, 2007; Kurz et al., 2008).
54 These passive walking robots necessarily have a wide base of support through either a wide "hip"
55 piece or wide "feet". This added mechanical stability is to control the inherent mediolateral (ML)
56 instability (Bauby and Kuo, 2000).

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

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

69 The amount of variability in gait has proven to be closely linked to the ability to maintain
70 upright stability (Brach et al., 2005; Brach et al., 2007; Maki, 1997). In one prospective study,
71 variability in the speed of gait between strides was shown to be the best predictor of falling in an
72 elderly population (Maki, 1997). Similarly, a more recent study found that an increase in the
73 amount of stance time variability was associated with higher incidence of mobility disability in
74 the elderly (Brach et al., 2007). In addition, Brach et al (Brach et al., 2005) found step width
75 variability to be associated with falls in elderly individuals. It has been suggested that the
76 increased amount of variability is associated with decreased motor control in the elderly (Buzzi
77 et al., 2003). Thus, an appreciation of variability gives a strong foundation for understanding the
78 upright stability of an individual during locomotion. Furthermore, it is possible to examine the
79 amount of variability in gait to infer active control (Bauby and Kuo, 2000). In addition, the
80 impact of active control of the ML direction is demonstrated when a combined impairment of
81 vision and the vestibular system results in a large amount of ML variability despite intact
82 proprioception; an effect that was not as drastic however in the AP direction (O'Connor and Kuo,
83 2009).

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

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

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

100

101 **METHODS**

102 *Subjects*

103 Twenty subjects were recruited for participation to perform a lateral stepping gait (Table
104 1; Figure 1). Of these twenty, a subpopulation of six individuals returned within 9 months for a
105 second visit to perform a typical AP progression gait to allow for inferential comparison. All
106 participants gave written, informed consent in accordance with our Medical Center's Institutional
107 Review Board. Inclusion criteria included cognitive ability to give written informed consent and
108 currently exercising 2-3 times a week. Exclusion criteria included inability to give written
109 consent, pregnancy, as well as any neurological, vestibular, or musculoskeletal conditions that
110 would affect the participant's typical gait.

111 **INSERT FIGURE 1 AND TABLE 1 ABOUT HERE**

112 *Study Protocol*

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

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

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

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

143 *Data Analysis*

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

158 **INSERT FIGURE 2 ABOUT HERE**

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

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

175

176 **RESULTS**

177 *Anteroposterior Progression Gait*

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

181 length of 144.27 ± 11.56 mm, standard deviation of 18.23 ± 5.90 mm, and CoV of 0.13 ± 0.04 .
182 The AP direction had an average length of 576.08 ± 49.74 mm, standard deviation of $19.69 \pm$
183 6.45 mm, and CoV of 0.03 ± 0.01 for the group.

184

185 *Lateral Stepping Gait*

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

188 Absolute Variability (Standard Deviation)

189 The standard deviation for the ML direction was significantly greater than the AP
190 direction for the trials with right leg lagging ($F_{1,19}=57.841$, $p<0.001$; Table 2 & 3) and left leg
191 lagging ($F_{1,19}=86.868$, $p<0.001$; Table 4 & 5). The standard deviation for the leading leg was
192 significantly greater than the lagging leg for right leg lagging trials ($F_{1,19}=87.263$, $p<0.001$) and
193 for left leg lagging trials ($F_{1,19}=28.856$, $p<0.001$). There was a significant interaction for both
194 right leg lagging trials ($F_{1,19}=61.010$, $p<0.001$) and for left leg lagging trials ($F_{1,19}=33.947$,
195 $p<0.001$).

196 Normalized Variability (Coefficient of Variation)

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

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

204

205 **DISCUSSION**

206 *Absolute versus Normalized Variability*

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

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

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

228 *Anteroposterior versus Mediolateral Control*

229 Based on the variability analyses, comparing AP and ML direction variability in a novel
230 gait task, it can only be concluded that the results did not support our hypothesis. Interpretation
231 of the absolute variability could lead to the conclusion of no distinct control differences between
232 directions. However, inconsistency between lag and lead step standard deviations in the AP
233 direction does not offer any insight into directional control, but rather highlights the dependency
234 of standard deviation on means. Thus, we consider the normalized variability, which portrays a
235 more detailed picture of the control differences for AP and ML direction. Specifically, the
236 change in the direction of progression of gait resulted in a greater amount of variability in the AP
237 direction than the ML direction. Closer inspection of the subpopulation's forward walking trials
238 leads to the interpretation that there is no difference in directional control (standard deviation) or
239 greater ML control with increased variability (CoV); this is exactly opposite to the lateral
240 stepping results. It seems without physical entities such as inertia and momentum assisting the
241 AP direction, the amount of variability for foot placement becomes larger in the AP direction
242 than the ML direction. It was not expected to see a difference in CoV of such magnitude between
243 the two planes. The magnitude of difference for AP compared to ML direction in the lateral
244 stepping gait was much greater and in opposite direction to the step CoV values for our
245 subpopulation that performed a typical AP progression walk (group mean AP: 0.03 ± 0.01 , ML:
246 0.13 ± 0.04). Brach et al (Brach et al., 2005) reported CoV measures for elderly non-fallers in
247 typical AP progression walking comparable to our subpopulation (group mean AP: $0.075 \pm$

248 0.034, ML: 0.156 ± 0.159). The large magnitudes of the CoV measures found for the lateral
249 stepping gait may be the result of the novelty of the task.

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

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

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

279 *Study Limitations*

280 Our results should be viewed in lieu of the following limitations. First, contrary to Bauby
281 and Kuo (2000), subjects were ambulating on a treadmill. As a result, the space constraints of the
282 treadmill as well as the motion of the treadmill belt may have influenced the measures. However,
283 other groups have previously concluded that treadmill gait results in similar variability
284 magnitudes as overground gait (Owings and Grabiner, 2004a), leading us to believe that the
285 directional results of our study would not be affected. Second, our study utilized variability to
286 infer active control similar to previous literature (Bauby and Kuo, 2000; O'Connor and Kuo,
287 2009). Future work should improve upon these findings by measuring active control through
288 other means. Third, our study aimed to compare the AP and ML variability during a lateral
289 stepping gait. Comparing the magnitudes of variability in the lateral stepping gait to a typical AP
290 progression gait is difficult due to lack of training in the lateral stepping gait. Future work should
291 attempt to address the novelty of the lateral stepping gait through possible training programs.
292 Finally, the preferred speed for the lateral stepping gait was considerably less than the one found
293 in typical AP progression walking. This was done, however, to permit individuals to walk at their

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

297

298 **CONCLUSION**

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

308

309 **ACKNOWLEDGMENTS**

310 This work was supported through funding from a NASA Nebraska EPSCoR Space Grant
311 and the University of Nebraska at Omaha's University Committee on Research and Creative
312 Activity Grant.

313

314 **Conflict of interest statement**

315 None of the authors have any conflict of interest.

316

317 **Abbreviations**

318 ML - mediolateral

319 AP - anteroposterior

320 Hz - Hertz

321 m - meter

322 s - second

323 CoV - coefficient of variation

324

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372

Table 1: Subject Demographics.

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

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383 **Table 2:** Average step lengths, standard deviations, and coefficient of variation for right leg
384 lagging trials for group (n=20).

385 Group means \pm standard deviation

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

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

392

Subject		Anteroposterior (AP)		Mediolateral (ML)		Subject		Anteroposterior (AP)		Mediolateral (ML)	
		Lag Step	Lead Step	Lag Step	Lead Step			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

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416 **Table 4:** Average step lengths, standard deviations, and coefficient of variation for left leg
 417 lagging trials for group (n=20).

418 Group means \pm standard deviation

	<i>Anteroposterior (AP)</i>		<i>Mediolateral (ML)</i>	
	<i>Lag Step</i>	<i>Lead Step</i>	<i>Lag Step</i>	<i>Lead Step</i>
419 <i>Average (mm)</i>	22.53 \pm 12.55	22.05 \pm 10.14	151.18 \pm 38.21	593.20 \pm 76.21
420 <i>Standard Deviation (mm)</i>	13.50 \pm 4.07	14.62 \pm 3.99	15.82 \pm 6.53	30.18 \pm 5.15
421 <i>Coefficient of Variation</i>	0.67 \pm 0.15	0.71 \pm 0.12	0.10 \pm 0.03	0.05 \pm 0.01

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

Subject		Anteroposterior (AP)		Mediolateral (ML)		Subject		Anteroposterior (AP)		Mediolateral (ML)	
		Lag Step	Lead Step	Lag Step	Lead Step			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 in step 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

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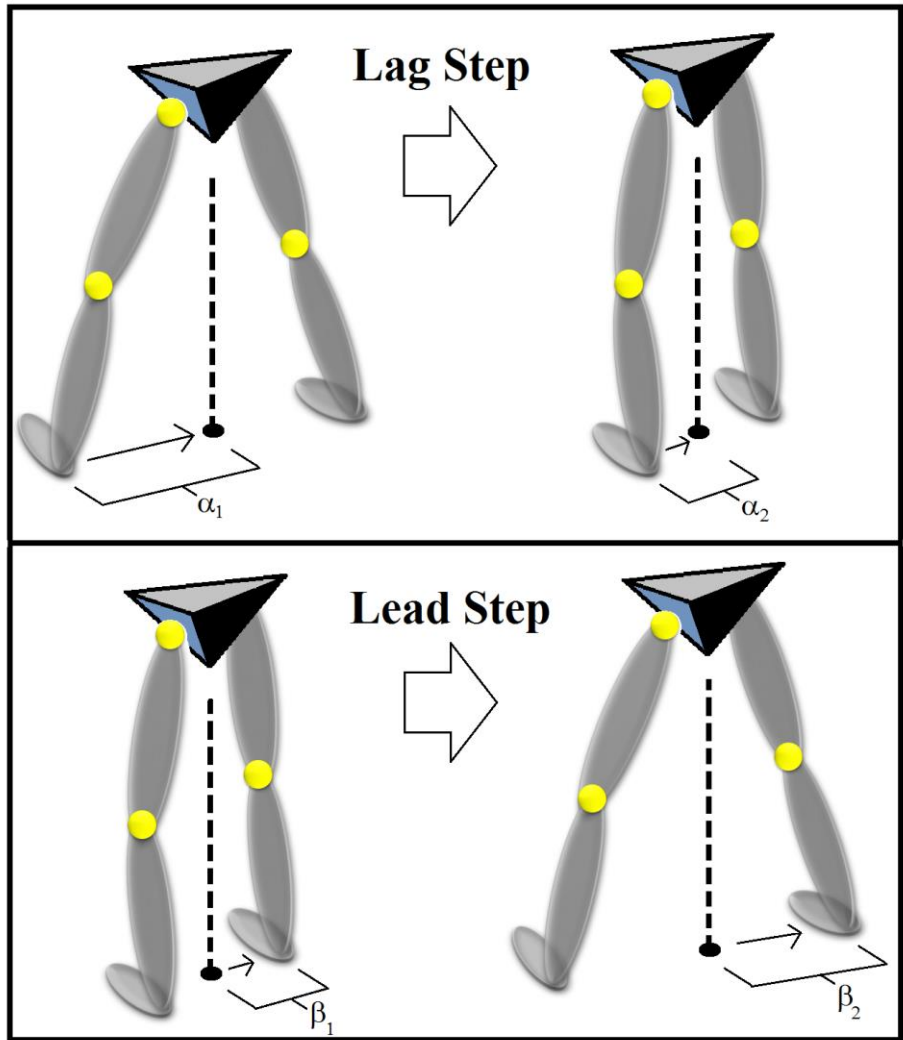


Figure 1: Lower limb diagram showing the lateral stepping gait for two different steps. (Top) The lag step shows the left leg stepping closer to the individual's center of mass (dropped down on dashed line) ($\alpha_2 < \alpha_1$). (Bottom) The lead step has the right foot stepping away from the individual's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

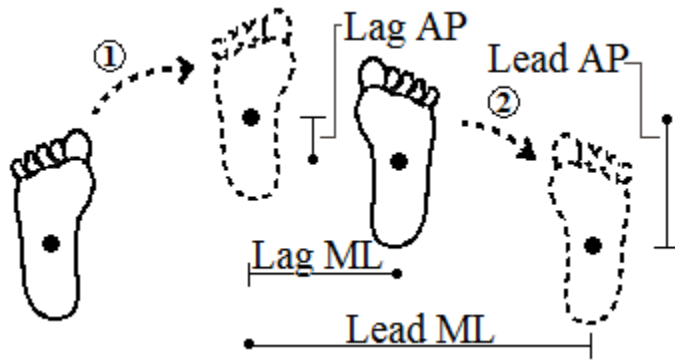


Figure 2: Lag and lead step measures in anteroposterior (AP) and mediolateral (ML) planes. The Lag AP and Lag ML are measured from the center of the leading foot's position to the center of the lagging foot's position following movement of the lagging leg. The Lead AP and Lead ML are measured from the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