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# Gait Measurement in Chronic Mild Traumatic Brain Injury: A Model Approach

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28 **Abstract**

29 **Introduction**

30 Mild traumatic brain injury (mTBI) can impact gait, with deficits linked to underlying neural  
31 disturbances in cognitive, motor and sensory systems. Gait is complex as it is comprised of  
32 multiple characteristics that are sensitive to underlying neural deficits. However, there is currently  
33 no clear framework to guide selection of gait characteristics in mTBI. This study developed a  
34 model of gait in chronic mTBI and replicated this in a separate group of controls, to provide a  
35 comprehensive and structured methodology on which to base gait assessment and analysis.

36 **Methods**

37 Fifty-two people with chronic mTBI and 59 controls completed a controlled laboratory gait  
38 assessment; walking for two minutes back and forth over a 13m distance while wearing five  
39 wirelessly synchronized inertial sensors. Thirteen gait characteristics derived from the inertial  
40 sensors were selected for entry into the principle component analysis based on previous  
41 literature, robustness and novelty. Principle component analysis was then used to derive domains  
42 (components) of gait.

43 **Results**

44 Four gait domains were derived for our chronic mTBI group (variability, rhythm, pace and turning)  
45 and this was replicated in a separate control cohort. Domains totaled 80.8% and 77.4% of  
46 variance in gait for chronic mTBI and controls, respectively. Gait characteristic loading was  
47 unambiguous for all features, with the exception of gait speed in controls that loaded on pace and  
48 rhythm domains.

49 **Conclusion**

50 This study contributes a four component model of gait in chronic mTBI and controls that can be  
51 used to comprehensively assess and analyze gait and underlying mechanisms involved in  
52 impairment, or examine the influence of interventions.

53

54 **KEYWORDS:** gait, mild traumatic brain injury, principle component analysis, inertial sensors

55

## 56 **1. Introduction**

57 Gait assessment is a simple marker for overall health, as it predicts quality of life, survival,  
58 cognitive decline and falls [1]. Gait becomes more difficult with age and neurological deficits,  
59 which cause transfer from automatic to cognitive (higher level) control to maintain performance,  
60 particularly with complex environments or tasks [2]. Gait is complex and multifactorial, and  
61 therefore cannot be captured by one characteristic, such as gait speed which is universally used  
62 to reflect gait due to its robust clinometric properties [3]. Gait is comprised of multiple  
63 characteristics including temporal, spatial and variability characteristics that can further  
64 discriminate pathological effects; therefore, measuring multiple gait characteristics is critical to  
65 examine specific features of disease or injury [2]. Despite this, most previous mild traumatic brain  
66 injury (mTBI) gait research has focused on singular gait characteristics (i.e. primarily gait speed)  
67 [4], likely due to the ease of measurement and to avoid multiple comparison statistical issues.  
68 Gait speed is an accumulation of many gait features and although it provides a measure of global  
69 performance and is sensitive to pathology and age [3], it is not specific and therefore may not  
70 reflect precise underlying deficits [5]. For example, gait speed is not discriminative or reflective of  
71 subtle and selective alterations in gait that occur due to injury or illness [6-8]. Selective  
72 identification of gait characteristics is vital for discrimination of pathology, identifying specific  
73 features of injury or disease progression and discerning the effect of pathology via detection of  
74 shared neural substrates for gait and other features (e.g. cognition, sensory function etc.) [2]. For  
75 example, different cognitive domains and brain regions have selective relationships to specific  
76 gait features (pace, variability, rhythm etc.) [2, 9], therefore examining multiple aspects of gait  
77 may help to uncover underpinning neural impairments due to mTBI. Additionally, those with  
78 chronic mTBI typically have persistent symptoms that do not relate to gait speed, but may relate  
79 to other discrete gait characteristics (i.e. turning performance) [10].

80 There are inconsistent reports of how gait is impaired in people with chronic mTBI. These mixed  
81 results could be due to the variable gait testing conditions (e.g. straight, turning, obstacle crossing,  
82 etc.), and gait characterization techniques (e.g. gait mats, camera-based motion capture, etc.),  
83 as well as limited cohorts involved (e.g. differing samples, small sample sizes, etc.). For chronic  
84 mTBI populations more than one year post injury, there are reports of no change or decrease of  
85 gait speed during straight gait and complex gait (e.g. obstacle crossing, uneven surfaces,  
86 crowded spaces etc.) under single and dual-task conditions [4]. Additionally, previous reports of  
87 increased double support time with chronic mTBI [4] has not been reproduced across two cohorts  
88 where age and mTBI history were matched [11, 12]. Similar trends for other spatiotemporal gait

89 characteristics, such as stride length, stride width, and stride time can be found throughout the  
90 chronic mTBI gait literature [4]. Some of the variability of these observations could be mitigated  
91 by comprehensively assessing gait through examination of gait domains accounting for many  
92 aspects of gait performance (e.g. pace, variability, rhythm, turning etc.) opposed to individual gait  
93 characteristics. Conceptual models of gait provide a simplified framework for grouping and  
94 selection of gait characteristics, which allow even small cohort studies to examine gait  
95 comprehensively through informed analysis of independent features of gait while avoiding  
96 redundancy.

97 A comprehensive range of gait characteristics is required to detect selective and specific neural  
98 substrate relationships [2]. However, an issue of measuring multiple gait characteristics is high  
99 covariance amongst the measures, suggesting redundancy of some characteristics and a need  
100 to identify key components for sensitivity and specificity of pathology. Therefore, conceptual gait  
101 models have been developed to eliminate redundancy by assisting with data reduction and  
102 interpretation, which group gait characteristics into domains [5, 7, 13-15]. Domains provide a  
103 useful structure to interpret underlying contributions of various pathological deficits to gait. Data  
104 reduction methods, such as exploratory factor analysis and principle component analysis (PCA),  
105 have previously been used to examine and explain other complex physiological processes (e.g.  
106 cardiovascular disease [16]), and have been used to derive statistically independent domains of  
107 gait in various cohorts. Development of a pathology specific gait model facilitates robust  
108 investigation into underlying mechanisms involved in gait impairment [8], which helps identify  
109 specific features that contribute to gait deficits and the influence of interventions or rehabilitation.  
110 To date, however, no model of gait has been developed for chronic mTBI, which limits the  
111 understanding of gait disturbance in this population. Previous studies have shown that depending  
112 on the population being studied (e.g. older adults, Parkinson's disease etc.) gait model domains  
113 may vary in terms of gait characteristics that load onto specific domains. For example, some gait  
114 characteristics (e.g. step and stance time variability) have been found to load onto multiple  
115 domains (e.g. Pace and Variability) in Parkinson's disease [13] but not in older adults [5].  
116 Therefore, a specific gait model that contains key outcomes with respect to chronic mTBI  
117 pathology is required to reduce data to allow comprehensive gait analysis and direct comparison  
118 to control groups in future studies in this population.

119 This study builds on earlier work in different cohorts that include older adults and Parkinson's  
120 disease [5, 7, 13-15, 17, 18] and uses PCA to derive independent gait domains in chronic mTBI.  
121 Additionally, this study validates the derived model in a separate group of age matched healthy

122 controls. Our aim was to determine a gait model in chronic mTBI to allow robust understanding of  
123 the underlying construct of gait in this population and to guide variable selection for future  
124 research (data reduction).

## 125 **2. Methods**

### 126 **2.1. Participants**

127 Subjects who had an mTBI with self-reported balance instability >3 months after their initial injury  
128 were recruited as part of a larger study evaluating chronic mTBI. A total of 52 participants with  
129 chronic mTBI and 59 age matched healthy controls were included in this study. Full details of the  
130 mTBI classification, recruitment process and study can be found elsewhere [19]. Briefly, inclusion  
131 criteria consisted of (1) were >3 months post mTBI with persistent balance complaints for the  
132 mTBI group, or had no history of brain injury in the past year for the control group, (2) had no  
133 cognitive deficits as determined by the Short Blessed Test (score  $\leq 8$ ), and (3) were between the  
134 ages of 18 and 60 years. Exclusion criteria consisted of musculoskeletal injury in the previous  
135 year that could have seriously impacted gait or balance; current moderate or severe substance  
136 abuse; any peripheral vestibular or oculomotor pathology from before their reported mTBI; or  
137 refusal to abstain from medications that could impact their mobility for the duration of testing.  
138 Participants were asked to abstain from medications that could impact their mobility starting 24  
139 hours prior to their first testing date. Prohibited medications included sedatives, benzodiazepines,  
140 narcotics pain medications and alcohol. All recruitment procedures were approved by the Oregon  
141 Health & Science University (OHSU) and Veterans Affairs Portland Health Care System  
142 (VAPORHCS) joint institutional review board and participants provided written informed consent  
143 prior to commencing the study.

### 144 **2.2. Clinical Assessment**

145 Age, sex, height (m) and mass (kg) were recorded for all of the participants. Symptom severity  
146 was measured using the Neurobehavioral Symptoms Index (NSI) [20]. Days since injury was also  
147 recorded for the mTBI group.

### 148 **2.3. Gait Assessment**

149 Participants wore five inertial sensors (Opals, v.1, APDM, Inc., 128Hz) strapped to their feet,  
150 lumbar (L5), sternum and head while they walked at their comfortable speed for two minutes back  
151 and forth over a 13m distance along a firm surfaced hallway.

## 2.4. Gait Characteristics for Principle Component Analysis

The rationale for inclusion of gait characteristics into our PCA was based upon the following;

- 1) **Metrics from MobilityLab:** To facilitate replication in future studies and in line with previous research [17, 18], only gait metrics that were automatically provided by MobilityLab (v.2) were included. Therefore, step length and asymmetry metrics were not included and standard deviations (SD) were used rather than coefficient of variability. SDs have also been used in previous gait models, as they are suggested to be easier for non-technical audiences to interpret [21].
- 2) **Metrics from Literature:** Earlier work that has investigated discrete aspects of gait in healthy controls and people with mTBI [4] highlighted that gait speed, stride length, stride time and double support time were the only variables widely examined in previous mTBI gait studies. We also examined previous gait models to include a sufficient number and range of gait characteristics and ensure the model accurately represented the underlying construct (gait) [14, 22, 23], while avoiding duplication and redundancy [5, 7, 13-15]. In line with other models we used single and double support time, rather than stance and swing time to avoid redundancy, as these features have been used in previous mTBI literature [4]. Additionally, we examined methodological factors and reliability of inertial sensor gait metrics to ensure robust metrics were included [24, 25].
- 3) **Metrics from Group Comparison:** Due to the limited range of gait metrics that have previously been assessed in mTBI populations, we examined the effect size of a comprehensive range of gait metrics between our chronic mTBI and control subjects to inform clinically useful metrics to enter into our gait model (Table 1). We also included several novel gait metrics, derived from the inertial sensors, which have not been included in previous gait models, such as foot angles and turning characteristics. Mean gait characteristics that had a  $d > 0.5$  effect size (i.e. medium effect size or greater) were considered for entry into the gait model, along with relevant SDs. All metrics that were considered for model entry are detailed above or shown in Table 1.

## 2.5. Data Analysis

Inertial sensor data were processed through MobilityLab (v.2, APDM, Inc.) [26] which provided the 16 gait characteristics included in statistical analysis. Data were analyzed in SPSS (v. 24, IBM, USA), checked for normality with Kolomogrov-Smirnov tests along with box-plots, with parametric analysis used. Means and SD described demographic data, with independent t-tests used for continuous data comparisons and Pearson Chi-square test used for frequency data

185 comparisons. Statistical tests were two-tailed with a  $p < 0.05$  considered significant. Gait data were  
186 described in terms of Mean and SD, with Cohen's effect sizes ( $d$ ) used to examine the magnitude  
187 of differences between groups, and to inform gait variable entry into our PCA. Gait variability  
188 characteristics were log transformed to improve normality of distribution, in line with previous  
189 research [5].

### 190 **2.5.1. Principle Component Analysis**

191 Principle component analysis was used to identify independent gait domains for mTBI. A varimax  
192 rotation was applied to derive orthogonal factor scores with a minimum eigenvalue for extraction  
193 set to 1 [27]. Scree plots, component loadings, item loadings and cross-loadings were examined.  
194 In line with previous gait models developed with a similar sample size [15], items that met a  
195 minimum loading of 0.60 were considered relevant to each domain. To validate our mTBI gait  
196 model (i.e. examine model robustness), we replicated the PCA analysis in a group of age-  
197 matched healthy controls.

## 198 **3. Results**

### 199 **3.1. Participants**

200 Demographic and gait characteristics of the mTBI and control participants are provide in Table 1.  
201 The mTBI group were on average 551 days since injury, with a wide range from 283 to 1013 days  
202 since injury reported. The NSI score showed that the mTBI participants were symptomatic  
203 compared with normative values (e.g. 6-13 [20]), and significantly symptomatic compared with  
204 the controls ( $p < .001$ ).

205 There were several impaired gait characteristics in mTBI compared with controls (Table 1),  
206 although some variability (SD) features had small ( $< 0.40$ ) effect sizes between the groups. Toe  
207 off angle ( $d = 0.07$ ) and number of steps performed when turning ( $d = 0.10$ ) had marginal effect  
208 sizes for differences between the groups, which highlighted that they may not be useful for mTBI  
209 populations and that we may need more sensitive or validated measures of these features.  
210 Therefore, toe off angle and number of steps when turning were not entered into the further PCA  
211 analysis.

### 212 **3.2. Principle Component Analysis**

213 Thirteen gait characteristics were entered into the PCA yielding four domains (Variability, Rhythm,  
214 Pace and Turning) that accounted for 80.8% of variance for mTBI gait and 77.4% of the variance  
215 for control gait. These findings highlighted that the mTBI gait model was replicated in the healthy



216 controls, with consistent between-component loadings between the groups. Within both groups,  
217 Variability accounted for the largest amount of variance in gait, followed by Rhythm, Pace and  
218 Turning (Table 2). The majority of gait characteristics loaded onto one domain (>0.600) for both  
219 groups, however gait speed cross-loaded onto both Rhythm (0.623) and Pace (0.630) domains  
220 for controls with higher loading onto Pace (Table 2). Cross-loading may indicate that gait speed  
221 and timing features of gait are linked.

## 222 **4. Discussion**

223 This is the first study to determine a conceptual gait model in those with chronic mTBI, which we  
224 replicated within a group of age-matched healthy controls. Such conceptual models of gait are  
225 useful to provide a simple framework for selecting and reducing gait characteristics for further  
226 analysis, which is particularly required when using wearable sensors that provide a plethora of  
227 gait outcomes. We confirmed the presence of four independent gait domains in chronic mTBI and  
228 controls, which supports the idea that gait is not a singular construct but is made up of  
229 independent characteristics. Previous studies have suggested that independence is due to  
230 different neural mechanisms (i.e. specific brain regions, processes or substrates) underpinning  
231 the separate gait domains [5, 9, 13]. Additionally, we demonstrated that when our gait model was  
232 applied to both mTBI and healthy controls, the domains remained the same, with similar levels of  
233 explained variance (i.e. mTBI 80.8% vs controls 77.4%), which is in line with previously developed  
234 gait models [5, 13]. This is vital to aid in examination of specific gait impairments with chronic  
235 mTBI.

### 236 **4.1. Gait Model Development**

237 Our gait model for chronic mTBI contained a comprehensive range of gait variables while avoiding  
238 redundancy. The selection of gait characteristics for the developed model was based on several  
239 factors, such as; a number of robust gait features, avoiding duplication and including measures  
240 previously reported in mTBI studies. We also included novel measures of gait (e.g. foot angles  
241 and turning) in our model, as these were available due to the use of multiple wearable inertial  
242 sensors (one on each foot and one at the waist) [26]. Of note, other studies have not been able  
243 to include turning or foot angle variables due reporting gait assessment with instrumented  
244 walkways or single inertial sensors [5, 7, 13-15, 17]. Likewise, measures not automatically  
245 exported through MobilityLab were not included. The use of inertial sensors, therefore, resulted  
246 in subtle but important differences in our gait model compared to previous models [5, 7, 13, 14].  
247 For example, similar to some previous gait models [7, 17], we did not include asymmetry within

248 our model as this feature was not automatically exported from MobilityLab. Nonetheless,  
249 asymmetry is not known to be a key feature of mTBI gait, unlike other pathological gait disorders  
250 (e.g. Parkinson's disease or Stroke) [2, 13, 15], and may be interesting to examine in future  
251 studies.

## 252 **4.2. Gait Model Domains**

253 The gait domains identified in this study were similar to previous models in older adults [5, 7] and  
254 Parkinson's disease [13, 15, 17], with variability, rhythm and pace being common amongst  
255 previous models. However, we found that explained variance in gait was slightly different between  
256 our model and previous models, as Variability accounted for the largest variance in the model,  
257 followed by Rhythm and Pace (Figure 1). Whereas other models have highlighted that pace or  
258 rhythm explained the most variance in older adults and pathological cohorts [5, 7, 13, 14, 17].  
259 Differences in explained variance compared to previous studies may have occurred due to our  
260 model involving a different pathology (i.e. mTBI vs Parkinson's disease [13, 15, 17]) and age  
261 range (i.e. previous studies were primarily in older adults [5, 7, 14]). Similarly, the current study  
262 involved a smaller cohort and used a lower number of gait characteristics in the model, i.e. 13  
263 compared to previous studies of 14 [2], 16 [5, 13], 18 [17] or 23 [14] characteristics. With the ability  
264 to derive turning metrics from the inertial sensors, we were able to derive a further independent  
265 domain of turning which emerged in both mTBI and control groups. In contrast, our recent  
266 Parkinson's gait model showed that pace and turning gait characteristics loaded onto the same  
267 domain [18], which highlights the importance of distinguishing independent gait features in  
268 different neurological groups. Turning being an independent domain of gait is an important finding  
269 for an mTBI cohort, as turning has been shown to be sensitive to mTBI pathology in both acute  
270 [28, 29] and chronic stages [10]. Interestingly, turning explained the least amount of variance of  
271 gait in the groups (mTBI: 17.4%, control: 14.7%), which suggests that we may need more  
272 sensitive measures to reflect this complex aspect of gait.

## 273 **4.3. Gait Model Validation**

274 The validation of our developed mTBI gait model was performed by conducting the same PCA in  
275 a separate healthy control cohort. The model was well replicated in the separate group, which  
276 highlighted that our model is robust and stable across those with and without pathology. As a  
277 result, the model can be used in future studies to directly assess differences in comprehensive  
278 but independent gait domains, through analysis of domains scores or selection of gait  
279 characteristics from independent domains. Nevertheless, there were some unexpected findings.  
280 Specifically, we found that while gait speed primarily loaded onto the Pace domain in both groups,

281 it also loaded onto the Rhythm domain in healthy controls, which has not been previously reported  
282 [5, 7, 13, 14], but may be linked to the statistical relationship between speed and timing features  
283 of gait. Similarly, while the same gait features loaded onto the same domains in both chronic mTBI  
284 and control groups, the factor loading weights were different. These important differences  
285 highlighted that the gait model was more discrete (e.g. no cross-loading of gait characteristics  
286 onto different domains) within the pathological population than controls, similar to previous gait  
287 models [5, 7, 13, 14]. Differences in our findings compared to previous studies may relate to the  
288 different instruments used to derive gait metrics (i.e. inertial sensors compared to pressure sensor  
289 mats) and inclusion of different gait features (i.e. double and single support time instead of stance  
290 and swing time). Despite this, the domains found for our chronic mTBI cohort were replicated in  
291 a separate age-matched healthy control cohort, with very similar levels of explained variance.

#### 292 **4.4. Future Directions**

293 In line with previous studies in other populations, our developed gait model simplifies gait  
294 measurement in mTBI, and demonstrates the independence of different gait characteristics [5, 7,  
295 13-15, 17, 18], such as variability, rhythm, pace and turning, but also addresses redundancy of  
296 features. Gait is often used as an outcome for studies that address the efficacy of treatments or  
297 therapeutics in mTBI [30, 31]. Studies of mTBI often adopt a detailed measurement of gait using  
298 sophisticated technologies and protocols that result in a wide range of metrics to select from [4,  
299 32-35], but despite this, gait is largely reported via a limited set of gait characteristics. Gait speed  
300 is primarily used across different neurological pathologies to report gait performance due to the  
301 ease and robustness of measurement [36], especially within clinical and laboratory settings for  
302 mTBI [37-39]. However, gait speed only reflect global gait performance and provides limited  
303 understanding of impairments seen in different pathologies [13], which is where a more  
304 comprehensive approach may add value. Similarly, gait characteristics, other than gait speed,  
305 may be useful for non-invasive discrimination between pathologies [40-42], with potential for gait  
306 to become a diagnostic tool for mTBI. Appropriate gait characteristics selection for mTBI studies  
307 would benefit from a more systematic and informed approach, which is where our developed gait  
308 model could add value to future studies. The primary benefit of a gait model for chronic mTBI is  
309 the reduced number of gait characteristics for further analysis, which avoids statistical issues with  
310 the number of variables examined (i.e. multiple comparisons) within cohorts of variable size.  
311 Researchers using the model can be confident that a wide range of characteristics are  
312 represented, while reducing analysis of redundant variables. Future studies can now use our  
313 developed gait model framework to select individual gait characteristics from independent gait

314 domains (e.g. double support time SD, double support time, stride length, turn duration) or  
315 combine gait characteristics within a domain using Z-scores for further analysis [8], or comparison  
316 to controls.

#### 317 **4.5. Study Strengths and Limitations**

318 This study has several strengths and limitations that should be noted. The strengths of this study  
319 include the use of a commercially available inertial measurement units and MobilityLab software  
320 to record gait. This allowed simple, quick and easy collection of quantitative gait data that in the  
321 future could be performed in a variety of environments (e.g. clinics, research laboratories, home  
322 or community settings etc.). Additionally, inertial sensors allowed for the inclusion of novel and  
323 clinically relevant gait features (i.e. turning and foot angles). Another strength was the inclusion  
324 of a separate cohort of healthy controls to replicate the gait model that was derived for our mTBI  
325 cohort, which provided validation of the gait model. Only one previous study has examined a gait  
326 model within two separate cohorts in the same study [15], as other previous models have either  
327 only examined gait models within a single cohort [7, 14] or have replicated their model in a  
328 separate study [5, 13].

329 The limitations of this study include the relatively small number of participants in each group, as  
330 the majority of previous gait model studies have included  $n > 100$  participants [5, 7, 13, 14].  
331 Previous statistical research has suggested large numbers (e.g.  $n > 100$ ) are required to  
332 adequately perform PCA [43], however it is recognized that in observational studies this sample  
333 size is challenging [44, 45]. Therefore, others have recommended that the variable to sample size  
334 ratio can be as low as 2-6 subjects for each variable (e.g. 2:1 ratio) [46-49], which will achieve  
335 appropriate component loadings if the structure of the model (and underlying concept) is strong.  
336 Additionally, in line with a previous gait model with a similar size cohort ( $n=60$ ) [15], to ensure  
337 robust domains we only considered variables that had component loadings  $> 0.60$  as opposed to  
338 larger cohort studies that have used  $> 0.50$  loadings to define variables loaded onto specific  
339 domains [5, 7, 13]. Another limitation was the lack of asymmetry gait variables included in the  
340 model. While measures of asymmetry may not be relevant to an mTBI population, they may  
341 provide a more comprehensive evaluation of gait, and could be included in future gait models.  
342 Finally, our mTBI cohort consisted of people who were still symptomatic  $> 3$  months following their  
343 injury, and it should be noted that the developed gait model (i.e. domains loadings) may change  
344 in those who are asymptomatic or at different mTBI stages (i.e. acute, sub-acute etc.), which could  
345 be examined in future studies.

## 346 **5. Conclusion**

347 This study presents a gait model to guide assessment and analysis of gait in chronic mTBI, which  
348 was replicated in a group of age-matched controls. We found that there were four domains of gait  
349 in chronic mTBI and controls, specifically Variability, Rhythm, Pace and Turning. The developed  
350 gait model provides a useful framework with which to assess the relationships between gait and  
351 the underlying mechanisms (or outcomes that represent these) of impairment. However, selection  
352 of gait characteristics in future analysis should be specific to pathology and the aims of  
353 investigation.

## 354 **Author Contributions**

355 SS was involved in: Conceptualization, Data Curation, Formal analysis, Investigation, Writing;  
356 original draft and all revisions, review and editing. LP, RM, DM and PCF were involved in: Data  
357 Collection, Methodology, Writing; review and editing. LAK was involved in: Obtaining Funding,  
358 Conceptualization, Methodology, Study Supervision, and Writing; review and editing.

## 359 **Conflict of Interest**

360 None to declare.

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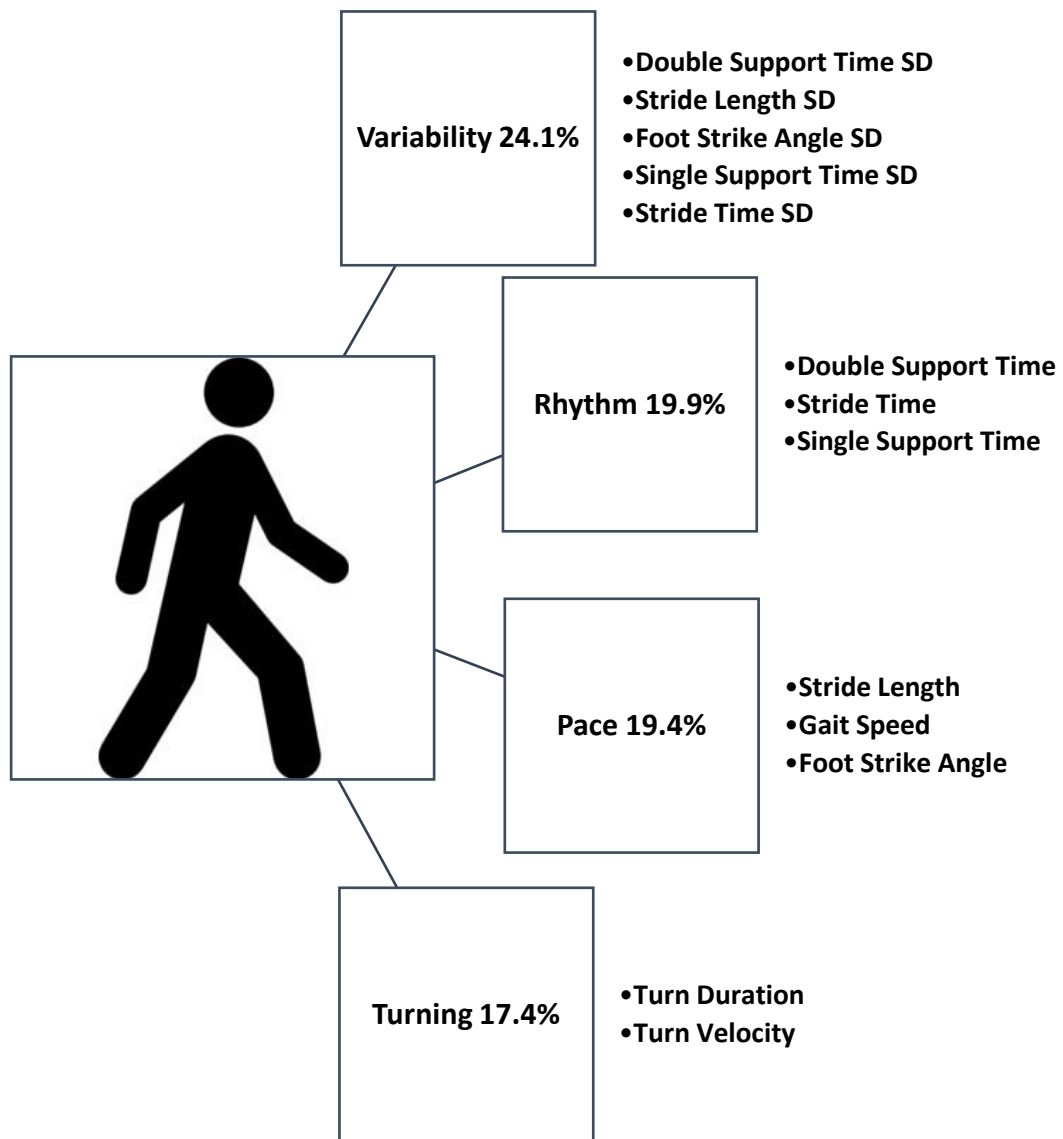
534 **Table 1 - Demographic and gait characteristics**

	<b>Chronic mTBI (n=52)</b>	<b>Controls (n= 59)</b>	<b>t</b>	<b>df</b>	<b>p</b>
Age (years)	39.56 (11.34)	36.96 (12.68)	1.14	110	.255
Height (m)	171.08 (9.51)	171.60 (9.55)	-0.29	110	.776
Weight (kgs)	79.69 (19.51)	76.10 (19.39)	0.95	110	.347
NSI score	36.51 (14.82)	3.92 (4.07)	16.23	110	<b>&lt;.001*</b>
Gender (m/f)	16 M / 37 F	25 M / 34 F	1.79 <sup>†</sup>	1 <sup>†</sup>	.239 <sup>†</sup>
Days since injury <sup>‡</sup>	551 (283, 1013)	-	-	-	-
	<b>Mean (SD)</b>	<b>Mean (SD)</b>			<b>d</b>
Stride Length (m)	1.22 (0.12)	1.30 (0.11)			0.70
Gait Speed (m/s)	1.09 (0.13)	1.21 (0.13)			0.93
Foot Strike Angle (°)	23.61 (3.61)	26.11 (3.76)			0.68
Toe off Angle (°)	39.35 (3.10)	39.56 (3.18)			0.07
Single Support Time (%GCT)	39.52 (1.33)	40.41 (1.40)			0.66
Double Support Time (%GCT)	10.49 (1.33)	9.61 (1.39)			0.65
Stride Time (s)	1.12 (0.07)	1.08 (0.07)			0.58
Foot Strike Angle SD (°)	1.66 (0.38)	1.56 (0.40)			0.26
Toe off Angle SD (°)	1.25 (0.36)	1.12 (0.53)			0.29
Stride Length SD (m)	0.04 (0.01)	0.04 (0.01)			0.00
Single Support Time SD (%GCT)	0.69 (0.16)	0.63 (0.13)			0.42
Double Support Time SD (%GCT)	1.07 (0.30)	0.96 (0.23)			0.42
Stride Time SD (s)	0.02 (0.01)	0.02 (0.01)			0.45
Turn Duration (s)	2.34 (0.44)	2.09 (0.37)			0.62
Turn Step Number (n)	3.61 (0.67)	3.54 (0.72)			0.10
Turn Velocity (°/s)	161.18 (33.68)	197.76 (43.55)			0.94

535 [<sup>‡</sup>= Median and Inter-quartile range: 25<sup>th</sup> and 75<sup>th</sup> percentiles, <sup>†</sup>Chi-square, mTBI = mild traumatic brain injury, m = meters, s =  
 536 seconds, %GCT = percentage of gait cycle time, n = number, ROM = range of movement]

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**Figure 1 - Gait Model for Chronic Mild Traumatic Brain Injury**

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542 **Table 2 – Principle Component Analysis of Gait Characteristics**

	Chronic mTBI (n=52)				Control (n=59)				
	Variability	Rhythm	Pace	Turning	Variability	Rhythm	Pace	Turning	
Double Support Time SD	<b>0.813</b>	-0.004	-0.418	-0.133	<b>0.815</b>	0.182	-0.247	0.185	
Stride Length SD	<b>0.789</b>	0.032	0.221	0.006	<b>0.823</b>	0.069	0.248	-0.212	
Foot Strike Angle SD	<b>0.783</b>	0.117	-0.127	0.229	<b>0.726</b>	-0.032	0.051	0.105	
Single Support Time SD	<b>0.777</b>	-0.033	-0.500	-0.146	<b>0.845</b>	0.167	-0.261	0.277	
Stride Time SD	<b>0.722</b>	0.173	-0.425	0.120	<b>0.612</b>	-0.201	-0.364	-0.097	
Double Support Time	0.070	<b>0.962</b>	-0.066	0.094	-0.195	<b>-0.905</b>	-0.063	-0.166	
Stride Time	0.044	<b>0.602</b>	0.110	0.561	0.167	<b>-0.699</b>	0.059	-0.283	
Single Support Time	-0.072	<b>-0.962</b>	0.077	-0.093	0.197	<b>0.907</b>	0.064	0.165	
Stride Length	-0.197	-0.186	<b>0.910</b>	-0.099	-0.128	0.285	<b>0.846</b>	0.062	
Gait Velocity	-0.187	-0.482	<b>0.695</b>	-0.373	-0.194	<b>0.623</b>	<b>0.630</b>	0.227	
Foot Strike Angle	-0.132	0.173	<b>0.664</b>	-0.168	-0.010	-0.311	<b>0.739</b>	0.165	
Turn Duration	-0.031	0.095	-0.162	<b>0.914</b>	-0.112	-0.252	-0.098	<b>-0.880</b>	
Turn Velocity	-0.085	-0.136	0.228	<b>-0.898</b>	0.087	0.298	0.219	<b>0.864</b>	
% Variance					% Variance				
(80.8% total)	24.1	19.9	19.4	17.4	(77.4% total)	24.1	22.8	15.8	14.7

543 [Bold text = component loading >0.60, m = meters, s = seconds, %GCT = percentage of gait cycle time, n = number, ROM = range of movement]