

# Free-living Turning Rather Than Gait Differentiates People with Chronic Mild Traumatic Brain Injury from Controls

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## Research

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# Abstract

**Background:** Physical function remains a crucial component of mild traumatic brain injury (mTBI) assessment and recovery. Traditional approaches to assess mTBI lack sensitivity to subtle deficits post-injury, which can impact quality of life, daily function and can lead to chronic issues. Inertial measurement units (IMU) provide an objective alternative for measuring physical function of gait and turning and can be used in any environment. Our recent work has found that turning quality is more sensitive than the quantity of physical activity when comparing chronic mTBI and healthy controls. However, no studies have compared the quality of free-living gait and turning characteristics concurrently in chronic mTBI and healthy controls. This study aimed to determine whether free-living gait or turning is more sensitive in differentiating chronic mTBI from controls.

**Methods:** Thirty-two people with chronic self-reported balance symptoms after mTBI (age:  $40.88 \pm 11.78$  years, median days post injury: 440.68 days) and 23 healthy controls (age:  $48.56 \pm 22.56$  years) were assessed for ~7 days using a single IMU at the waist on a belt. Free-living gait and turning characteristics were evaluated for chronic mTBI and controls using multi-variate analysis. Receiver operating characteristics (ROC) and Area Under the Curve (AUC) analysis were used to determine outcome sensitivity to chronic mTBI.

**Results:** Free-living gait characteristics were not different in chronic mTBI and controls (all  $p > 0.05$ ). In contrast, all but two (number of turns and average velocity CV) free-living turning characteristics were significantly different between chronic mTBI and controls, whilst controlling for age and sex (Bonferroni adjusted  $p < 0.002$ ). The chronic mTBI group had larger turn angles and longer turn durations compared to controls. ROC and AUC analysis showed turn duration (AUC = 0.92) was the most sensitive measure for differentiating chronic mTBI from controls.

**Conclusions:** Results show that turning rather than gait characteristics were significantly different between chronic mTBI and controls, with turn duration being the most sensitive measure. These results suggest turning is a suitable surrogate biomarker to assess and monitor chronic mTBI.

## 1. Introduction

Traumatic Brain Injuries (TBI) can be broadly defined as sudden trauma causing damage to the brain, with severity ranging from mild TBI (mTBI; commonly known as concussion) to severe TBI [1]. An array of impairments accompany TBI, such as deficits in physical (balance, gait and turning) [2,3], psychological (cognitive impairments and symptoms) [4], and sensory function (visual or vestibular deficits) [5]. Such deficits can be subtle and difficult to detect in mTBI and may persist for long periods after the initial injury or hospital treatment (e.g. >3 months). Chronic symptoms post-mTBI can significantly impact quality of life and daily function, which can lead to prolonged issues/symptoms [6]. Physical impairments are particularly prevalent in mTBI, with eight out of ten people with acute mTBI reporting balance impairments within a few days of the injury and three out of ten reporting longer-term (chronic) balance

or gait impairments [5,7,8]. Therefore, physical testing (balance and gait) remains a crucial component of clinical assessment to quantify impairment through acute and chronic mTBI [9–12], which may provide targets for rehabilitation and continued physical function monitoring.

Following acute mTBI balance impairment is commonly assessed [13,14], primarily using the Balance Error Scoring System (BESS), which consists of a clinician manually recording errors each time the patient fails to maintain a balance stance position. However, the sensitivity of the BESS is highly variable due to considerable subjectivity in error counting that impacts the replicability and validity of results [15–17]. Additionally, subtle balance deficits may be visually undetectable by clinician's subjective assessment and therefore unmeasurable. Other physical impairments, such as gait deficits, are not often examined by clinicians following acute mTBI. Tandem walking may be done as part of the sports concussion assessment tool (SCAT), however clinician observation has been found to miss subtle deficits in mobility that persist in chronic mTBI (i.e. due to low ceiling effect of the test) [18]. To detect subtle gait deficits following mTBI, gait assessment is typically conducted in research settings with sensitive laboratory equipment, such as force plate and 3D motion capture [7,19–22].

Laboratory-based gait studies have primarily found pace-related gait deficits (stride length and gait speed) in chronic mTBI compared to healthy controls [23], suggesting gait may be a useful diagnostic marker. Additionally, Fino et al. 2018 [2] highlighted that more challenging mobility tasks elicit more gait impairments in mTBI (acute and chronic) compared to healthy controls [2,24]. However, previous laboratory studies have reported on a limited set of gait characteristics, such as only gait speed [2,25–28]. Therefore, laboratory assessment methods may fail to capture mTBI-related deficits that may occur within usual mobility within habitual (free-living) environments, which include including many non-linear paths or turns. Indeed, humans typically perform more complex mobility and over 1000 turns or subtle deviations per day within their usual daily lives [29,30]. Therefore, monitoring of mobility within free-living environments may provide useful metrics to detect subtle deficits following an mTBI.

Physical monitoring beyond the laboratory is becoming more common, due to the widespread use of discrete inertial-based measurement units (IMU), which are the accepted standard for gathering continuous, high-resolution data [31]. IMUs can estimate physical activity (e.g. steps per day) and balance, gait and turning impairments within any environment [2,14,32–35]. Our recent work examined free-living physical activity and turning in chronic mTBI patients and controls, with turning metrics found to be more sensitive than physical activity metrics to differentiate groups [3]. Specifically, those with mTBI had larger, longer and more variable turns during daily life, but had similar number of steps per day to controls [3]. Although previous studies have examined mTBI gait and turning ability in research settings, no study to date has comprehensively quantified free-living gait and turning characteristics concurrently in chronic mTBI and healthy controls. Therefore, the free-living mobility characteristics that are most sensitive to differentiate chronic mTBI patients from healthy controls remain unclear. Greater understanding of how mobility is affected in free-living environments may uncover useful markers for subtle deficits in chronic mTBI.

The aims of this study were to; 1) Compare free-living mobility (gait and turning) between chronic mTBI patients and healthy controls; and 2) Determine the most sensitive free-living mobility measures (gait and turning) that differentiate chronic mTBI from controls. We hypothesised that free-living mobility would be impaired in chronic mTBI compared to controls, with selective metrics sensitive to differentiation of chronic mTBI from controls.

## 2. Methods

### Participants

Thirty-two symptomatic chronic mTBI patients and 23 healthy controls participated, demographics are shown in Table 1. Ethical approval was granted by the Oregon Health and Science University (OHSU) and Veterans Affairs Portland Health Care System (VAPORHCS) joint institutional review board with participants providing written informed consent before commencing the study.

### Inclusion and Exclusion Criteria

Participants were included in the chronic mTBI group if they had had a diagnosis of mTBI based upon VHA/DoD [36] criteria and who were greater than three months post mTBI with self-reported balance impairments. The control group consisted of those who had no history of brain injury in the last year. Additionally, mTBI participants were required to have no cognitive deficits as determined by the Short-Blessed Test (score <8) [37]. Participants were excluded if they; had any musculoskeletal injury which could impair their gait or balance, a recent history of moderate or severe substance abuse and for the mTBI group, any peripheral vestibular or oculomotor pathology preceding their mTBI.

### Gait and turning analysis

Participants were asked to wear an IMU for 7 days, and participants with less than 3 days were excluded, in line with previous studies [3,29,38]. Participants wore a compact (L×W×H: 43.7×39.7×13.7 mm, 128 Hz) and lightweight (<25 grams) IMU attached to a belt (Opal V1, APDM Inc., Portland, OR) that contained an accelerometer ( $\pm 16g$ ,  $\pm 200g$ ), gyroscope ( $\pm 2000$  deg/s) and magnetometer ( $\pm 8$  Gauss). Participants wore the IMU around their waist for a minimum of 5 hours per day for up to 7 days using the protocol described previously by Fino et al 2017 [39] and Stuart et al 2020 [3]. Data was stored on the IMU internal storage (8Gb) and then downloaded via proprietary software to a laptop. Free-living data were processed using two separate custom-made and validated MATLAB<sup>®</sup> (MathWorks Inc, Massachusetts, USA) algorithms to estimate free living *Turning* and *Gait* characteristics [29,38,40,41].

#### ***Turning.***

Movement bouts were calculated for free living turning [3] using a bespoke MATLAB® as previously described [3]. Briefly, turning events were detected using the horizontal rate of the waist sensor,  $>15^\circ/\text{sec}$  represented a turn, with the start and end of turns set to point where rate dropped below  $5^\circ/\text{sec}$ , with a minimum of  $45^\circ$  trunk rotation around the vertical plane and duration of 0.5-10 secs required for classification. Integration of the angular rate of the waist sensor about the vertical axis was used to define relative turn angles. Turning characteristics included number of turns per hour, average turn angle ( $^\circ$ ), peak turn velocity ( $^\circ/\text{sec}$ ), average turn velocity ( $^\circ/\text{sec}$ ), turn duration (sec) and coefficient of variation (CV) of these measures.

## ***Gait:***

Free living gait characteristic was calculated using a separate bespoke MATLAB® algorithm (MathWorks Inc, Massachusetts, USA) as follows. Placement of the IMU on the waist examined orientation and periods of static and dynamic activity [40,41]. Subsequently, the latter were examined for initial and final contact events within the gait cycle via the continuous wavelet transform [42], where a bout/period of walking was predefined by a time period of between 0.25 and 2.25 seconds and  $\geq 3$  steps [43]. For the purposes of this study, a movement bout was classified as  $>10$  seconds. Gait characteristics included mean; stance time (seconds, s), step time(s), stride time (s), swing time (s), stride length (centimetres, cm), stride velocity (centimetres per second,  $\text{cms}^{-1}$ ) and coefficient of variation (CV) of these measures.

## **Self-Reported Symptoms**

Chronic mTBI patients completed the NSI symptom questionnaire, which is widely used in assessment of mTBI symptoms [23,44]. The NSI and subscales [45] have acceptable reliability in characterising presence and tracking severity of symptoms in TBI [45,46]. Therefore, the NSI is widely used in clinical practice and remains the cornerstone of clinical symptom assessment and supports the use as reference in this study.

## **Statistical Analysis**

Data were analysed in SPSS (v23, IBM) and R studio (R. RStudio, Boston, MA, USA). All data were normally distributed as assessed with Shapiro-Wilks tests before conducting parametric tests. Independent t-tests were performed comparing demographic information between mTBI and control groups. To compare free-living mobility in chronic mTBI to controls, we used separate multivariate analysis of covariance (MANCOVA) that controlled for sex and age [4,47].

To estimate which features of gait and turning differentiated chronic mTBI from controls, we used receiver operating characteristic (ROC) and area under the curve (AUC). ROC analysis in Figure 1 provides a trade-off between specificity (x axis) and sensitivity (y axis) between the various free-living mobility

characteristics and binary classification of either mTBI and healthy control. As such the measures with a high sensitivity or true positive can be seen on the upper left-hand side.

Statistical significance was determined at  $p < 0.05$  unless otherwise stated. Bonferroni corrected significance values were applied for multiple comparisons in free living characteristics ( $p < 0.002$ ). Effect sizes were described as interpreted as weak ( $< 0.50$ ), moderate ( $0.50 - 0.79$ ) or strong ( $> 0.80$ ) as previously described [48].

### 3. Results

## Demographics and Clinical Assessments

Demographic characteristics are presented in Table 1. For age (years), height (cm), mass (kg) and the number of days since injury (in mTBI group). Additional characteristics are presented for the Neurobehavioral Symptom Inventory (NSI) [49]. A higher score indicates a more severe or worsened symptom profile in the NSI (out of 88). In our mTBI cohort, NSI total score was moderately high (5<sup>th</sup> to 9<sup>th</sup> percentile) compared to previously published normative mTBI scores, demonstrating that our chronic mTBI group were symptomatic [45]. Participants were asked to wear the IMU sensor for 7 days, but compliance was variable across both groups with several mTBI ( $n=16$ ) and control ( $n=13$ ) participants wearing the sensor for less than 7 days. Specifically, the mean number of days that the IMU was worn was  $6.8 (\pm 2.4)$  days in the mTBI group and  $6.04 (\pm 2.0)$  days in the control group.

## Group differences in free-living gait and turning metrics

There were no significant differences in free-living gait between chronic mTBI ( $p > 0.05$ ) and controls, whilst controlling for age and sex (Table 2). Our results do show non-significant differences for mean values in mTBI and controls, with lower stance time ( $0.83s \pm 0.05$ ,  $0.85 \pm 0.09$ ), step time ( $0.70s \pm 0.05$ ,  $0.73 \pm 0.09$ ), stride time ( $1.41s \pm 0.10$ ,  $1.45 \pm 0.18$ ), and swing time ( $0.58s \pm 0.05$ ,  $0.60 \pm 0.09$ ) in mTBI compared to controls, respectively. In contrast, mean step length ( $74.01cm \pm 4.10$ ,  $72.68 \pm 3.60$ ), mean step velocity ( $105.59cm/s \pm 8.88$ ,  $101.34 \pm 11.47$ ), step length variability ( $18.62cm \pm 1.18$ ,  $18.32 \pm 0.96$ ) and step velocity variability ( $36.90cm/s \pm 3.11$ ,  $35.48 \pm 4.08$ ) were higher in the chronic mTBI compared to controls, respectively. Whereas, stance time variability, step time variability and stride time variability were equivalent in chronic mTBI and controls.

There were significant differences between chronic mTBI ( $n=32$ ) and control ( $n=23$ ) groups across all turning variables ( $p < 0.002$  Bonferroni corrected) except for the number of turns per hour ( $p = 0.01$ ) and average velocity variability ( $p = 0.03$ ), whilst controlling for age and sex (Table 2). Mean values for number of turns per hour ( $84.36 \pm 33.38$ ,  $60.00 \pm 23.83$ ), turn angle ( $97.84^\circ \pm 3.67$ ,  $82.02 \pm 12.62$ ), turn duration ( $1.73s \pm 0.11$ ,  $1.13 \pm 0.39$ ) and turn peak velocity variability ( $90.36 \pm 0.03$ ,  $0.32 \pm 0.02$ ) were all higher in mTBI compared to controls, respectively. Contrastingly, turn peak velocity ( $97.52^\circ/s \pm 8.80$ ,

149.84 ± 40.09) and turn average velocity (49.10°/s ± 4.18) were lower in chronic mTBI compare to controls, respectively.

Table 1  
Participant demographics

	<i>Controls</i> ( <i>n</i> = 23)	<i>mTBI</i> ( <i>n</i> =32)	<i>p</i>
Age ( <i>years</i> )	48.56 (22.56)	40.88 (11.78)	0.11
Sex (Male or Female) <sup>b</sup>	M(6) F(17)	M(6) F(26)	0.52
Height ( <i>cm</i> )	165.46 (8.03)	168.51 (9.19)	0.22
Mass ( <i>kg</i> )	68.03 (15.32)	76.17 (18.80)	0.25
NSI Total Score	-	35.88 (13.9)	-
NSI Vestibular	-	5.44 (2.22)	-
NSI Somatosensory	-	10 (4.92)	-
NSI Cognitive Score	-	8.34 (3.89)	-
NSI Affective Score	-	10.34 (5.64)	-
Days Since Injury <sup>a</sup> ( <i>n</i> )	-	440.68 (700.63)	-
<sup>a</sup> Median and interquartile range. <sup>b</sup> chi-squared, Mean and standard deviation reported unless otherwise stated. mTBI, mild traumatic brain injury; NSI – neurobehavioral symptom inventory			

Table 2

Free-living gait and turning characteristics; group differences whilst controlling for age and sex, Area under the Curve (AUC)

<i>Free-living gait metric</i>	<i>mTBI (n=32) Mean (S.D.)</i>	<i>Controls (n=23) Mean (S.D.)</i>	<i>F</i>	<i>p</i>	$\eta_p^2$	<i>AUC</i>
Mean stance time (seconds, s)	0.83 (0.05)	0.85 (0.09)	0.19	0.66	0.00	0.44
Mean step time (s)	0.70 (0.05)	0.73 (0.09)	0.21	0.65	0.00	0.44
Mean stride time (s)	1.41 (0.10)	1.45 (0.18)	0.21	0.65	0.00	0.44
Mean swing time (s)	0.58 (0.05)	0.60 (0.09)	0.22	0.64	0.00	0.44
Mean stride length (centimetres, cm)	74.01 (4.10)	72.68 (3.60)	2.84	0.10	0.05	0.63
Mean stride velocity (cms <sup>-1</sup> )	105.59 (8.88)	101.34 (11.47)	1.37	0.25	0.03	0.60
Stance time variability CV (s)	0.20 (0.01)	0.21 (0.02)	0.03	0.87	0.00	0.49
Step time variability CV (s)	0.20 (0.01)	0.20 (0.02)	0.10	0.75	0.00	0.48
Stride time variability CV (s)	0.22 (0.01)	0.22 (0.01)	0.35	0.56	0.01	0.51
Swing time variability CV (s)	0.20 (0.01)	0.21 (0.02)	0.13	0.72	0.00	0.47
Step length variability CV (s)	18.62 (1.18)	18.32 (0.96)	2.30	0.14	0.04	0.61
Step velocity variability CV (cms <sup>-1</sup> )	36.90 (3.11)	35.48 (4.08)	1.18	0.28	0.02	0.60
<i>Free-living turning metric</i>						
No. turn/hour (n/hr)	84.36 (33.38)	60.00 (23.83)	6.64	0.01	0.12	0.74
Angle (°)	97.84 (3.67)	82.02 (12.62)	67.53	0.00*	0.57	0.85
Angle CV (°)	0.49 (0.03)	0.38 (0.9)	46.85	0.00*	0.48	0.83
Duration (seconds)	1.73 (0.11)	1.13 (0.39)	80.32	0.00*	0.61	0.92
Duration CV (seconds)	0.42 (0.02)	0.36 (0.07)	17.62	0.00*	0.28	0.82
Peak velocity (°/second)	97.52 (8.80)	149.84 (40.09)	60.91	0.00*	0.54	0.11
Peak velocity CV (°/second)	0.36 (0.03)	0.32 (0.03)	15.56	0.00*	0.23	0.81
Average velocity	49.10 (4.18)	73.45 (18.63)	59.57	0.00*	0.54	0.11

(°/second)						
Average velocity CV (°/second)	0.34 (0.02)	0.32 (0.04)	4.82	0.03	0.09	<i>0.79</i>
<p>Bolded p values; <math>p &lt; 0.05</math> (Bonferroni corrected <math>p</math> value 0.002). Group analysis of covariance results controlling for age and sex. mTBI, mild traumatic brain injury; S.D., standard deviation; CV, coefficient of variation, <math>\eta_p^2</math> partial eta squared of effect size, F Wilks' <math>\lambda</math>,</p>						<p>AUC &gt; 0.50 in italics and bold.</p>

## Sensitivity and specificity of free-living gait and turning metrics

Figure 1 shows the receiver operating characteristics (ROC) analysis for the top two turning and gait characteristics. Free-living turning (mean AUC: 0.66) was substantially more sensitive than gait (mean AUC: 0.51) at differentiating chronic mTBI from controls (AUC > 0.50, Table 2). Turn duration (AUC: 0.92) was the most sensitive measure to distinguish chronic mTBI from controls.

### 4. Discussion

This study progresses our previous work [3], providing comprehensive examination of free-living gait and turning characteristics concurrently measured by a single IMU in those with chronic mTBI and healthy controls. Our results demonstrate that free-living turning is more sensitive than free-living gait in differentiating chronic mTBI from controls, with turn duration being the most sensitive outcome. Free-living assessment in mTBI is still an emerging research area, but these results coupled with those from other neurological conditions (e.g. Parkinson's disease) suggest that impaired turning occurs with neurological dysfunction [50]. Assessment of free-living mobility in chronic mTBI may allow for improved diagnostics and monitoring of recovery, as well as development of individualised and targeted rehabilitation.

### Free-living turning is impaired in chronic mTBI

Previous research has shown that physical impairments can be particularly prevalent in mTBI, due to the disruption in cognitive processing required to perform mobility such as turning and walking [5,7,8]. In agreement with our hypothesis, our results show that free-living turning was impaired in chronic mTBI compared to controls. Altered free-living turning in chronic mTBI expands upon previous results that have highlighted the importance of measuring turns in this cohort [3,51]. Turning is particularly relevant to mTBI due to the requirement of combined cognitive, sensory and motor processing that can be impacted by an mTBI [23,40,42]. Therefore, monitoring of turning can provide key metrics to monitor mTBI impairments, which is achievable in free living assessment as humans perform over 1000 turns per day [29,30].

Our results are consistent with our previous study in a smaller number of this mTBI cohort, which showed that free-living turn angle, duration, velocity and variability are impaired in chronic mTBI compared to healthy controls [3]. Greater turn duration, velocity, variability and angle may reflect reduced dynamic balance control in chronic mTBI that may impact confidence in turning [51]. For example, those with chronic mTBI may take more time to turn, and have more variability whilst avoiding smaller/quicker turns which may induce unwanted symptoms [51]. In contrast to our previous study, which incorporated in a smaller sample of this chronic mTBI cohort, there were no significant differences in the number of turns exhibited in those with chronic mTBI [3]. This suggests that other turning characteristics are better at distinguishing mTBI from healthy controls. As such those with chronic mTBI may be able to complete a comparable number of turns compared to controls, but the deficits from mTBI impact the quality of turning.

Our findings do corroborate with our previous free-living [3] and laboratory-based studies [51] that have shown peak turning velocity and average turning velocity to be impaired (lower) in the chronic mTBI group. Previous research from laboratory-based assessment has found that individuals with chronic mTBI may reduce their turning velocity due to impaired head stabilisation and mTBI symptoms [51]. Head stabilisation or coordination has yet to be explored fully in free-living environments, but it is reasonable that this coupling or coordination is also reduced in free-living environments and may explain the similarities seen in reduced peak turning velocity in people with chronic mTBI. Further work is required to examine and understand the origin of free-living turning deficits.

## **Free living gait characteristics are not impaired in chronic mTBI**

Lack of significant differences and low effect sizes in gait characteristics between chronic mTBI and health controls may be related to the considerable chronicity (median 1.2 years post injury) of this mTBI cohort. Meaning this cohort of chronic mTBI may have developed compensation strategies over-time to replicate 'normal' gait patterns during walking in their daily life, whereas turning may require more cognitive or sensory processing, which may be a complex task that is difficult to compensate for and therefore turning reveals subtle mobility deficits [23,33,53]. As such, we would expect if we tested these participants in the laboratory under complex conditions (e.g. dual-task, obstacle walking, turns course etc.), we might detect more deficits in gait between chronic mTBI and controls. More longitudinal analysis of chronic mTBI patients during different stages of recovery (acute to chronic) would be beneficial to monitor impairments and recovery in free-living mobility characteristics.

Currently, there is no definitive way of objectively understanding the reasons for lack of differences in free-living gait between our chronic mTBI and healthy control cohorts, as there are many unknown factors that affect free-living assessments. For example, not knowing the environments people were regularly walking in, the surfaces they walked on, or the types of terrain encountered [54]. Equally, it is not possible to quantify the usual free-living mobility habits of the participants or if this cohort display any

compensatory behaviour strategies (e.g. refraining from talking or performing other tasks whilst walking). The introduction of egocentric video recordings of free-living mobility may allow for better understanding and a robust reference [55]. If used in conjunction with objective free-living IMU assessment, video assessment could yield even greater understanding of free-living gait performance and any compensatory behaviour mTBI patients display within an environment.

## Strengths and limitations

The primary strength of this study was the use of a single IMU to objectively measure free-living gait and turning in chronic mTBI patients and controls, as the use of a single device and assessment within usual daily life means that subjects had low research burden. However, the outcome measures presented are primarily research-orientated, requiring a great deal of time-consuming post-processing and checking, which is based on prior experience of inertial data [57,58]. Therefore, there needs to be refinement and deployment of software that clinicians and patients can easily navigate, which would allow more widespread uptake and use by health professionals [58]. Participants were assessed for ~7 days using a single IMU attached to a waist belt. However variation in the exact length of time participants wore wearables (minimum three days) could introduce differences and therefore not reflect true habitual free-living mobility as used in other studies [50,59]. Using multiple IMUs may provide more detailed spatial and temporal data for turning, balance and gait as used in previous studies [23], but this carries different limitations; such as longer data download, processing complexity and increased wearer burden, limiting the practical or clinical application. This trade-off should be considered in future studies as a potential improvement to the assessment protocol. [60,61].

There were some additional limitations to this study. Firstly, a more detailed demographic profile could be reported in future studies to derive further inferences about the free-living mobility results or underlying physiological mechanisms for persistent symptom and mobility deficits [23]. For example, the symptom questionnaires were limited to NSI that were only completed by the mTBI cohort, which limited any useful comparisons and inference on the relationship between groups [3]. Secondly, balance problems in the chronic mTBI were self-reported with no baseline or robust analysis done to quantify the magnitude of impairment [3], with the many factors such as the previous history of mTBI and evidence of abnormal neuroimaging omitted [4,56]. Thirdly, the differences in this mTBI cohort's chronicity are likely to limit the direct comparison with other studies. Our study's cohort was chronic with a median post-injury time greater than 1-year, which compared to other studies examining people post-mTBI is a long time since injury [23,51].

## Conclusions

Our study has shown that a single IMU can obtain continuous free-living gait and turning measures, in symptomatic chronic mTBI and healthy controls. Results demonstrate that turning rather than gait characteristics were significantly different in chronic mTBI compared to controls. Therefore, turning could

be useful for diagnostics or monitoring of mTBI, and may provide a target for individualised rehabilitation strategies.

## **Declarations**

## **Ethics approval and consent to participate**

Ethical approval was granted by the Oregon Health and Science University (OHSU) and Veterans Affairs Portland Health Care System (VAPORHCS) joint institutional review board with participants providing written informed consent before commencing the study.

## **Consent for publication**

n/a.

## **Availability of data and materials**

De-identified data generated from this study will be deposited into the Federal Interagency Traumatic Brain Injury Research (FITBIR) Informatics System.

## **Competing interests**

All authors declare that they have no competing interests.

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## **Author contributions**

DP was responsible for writing the manuscript, editing, statistical and data analysis. AG was responsible for data analysis, editing and reviewing the manuscript. LP, KRC and LAK were responsible for data collection and reviewing the manuscript. SS was responsible for data analysis, writing, statistical analysis and reviewing the manuscript.

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## Figures

## Receiver Operator Characteristic (ROC) Analysis

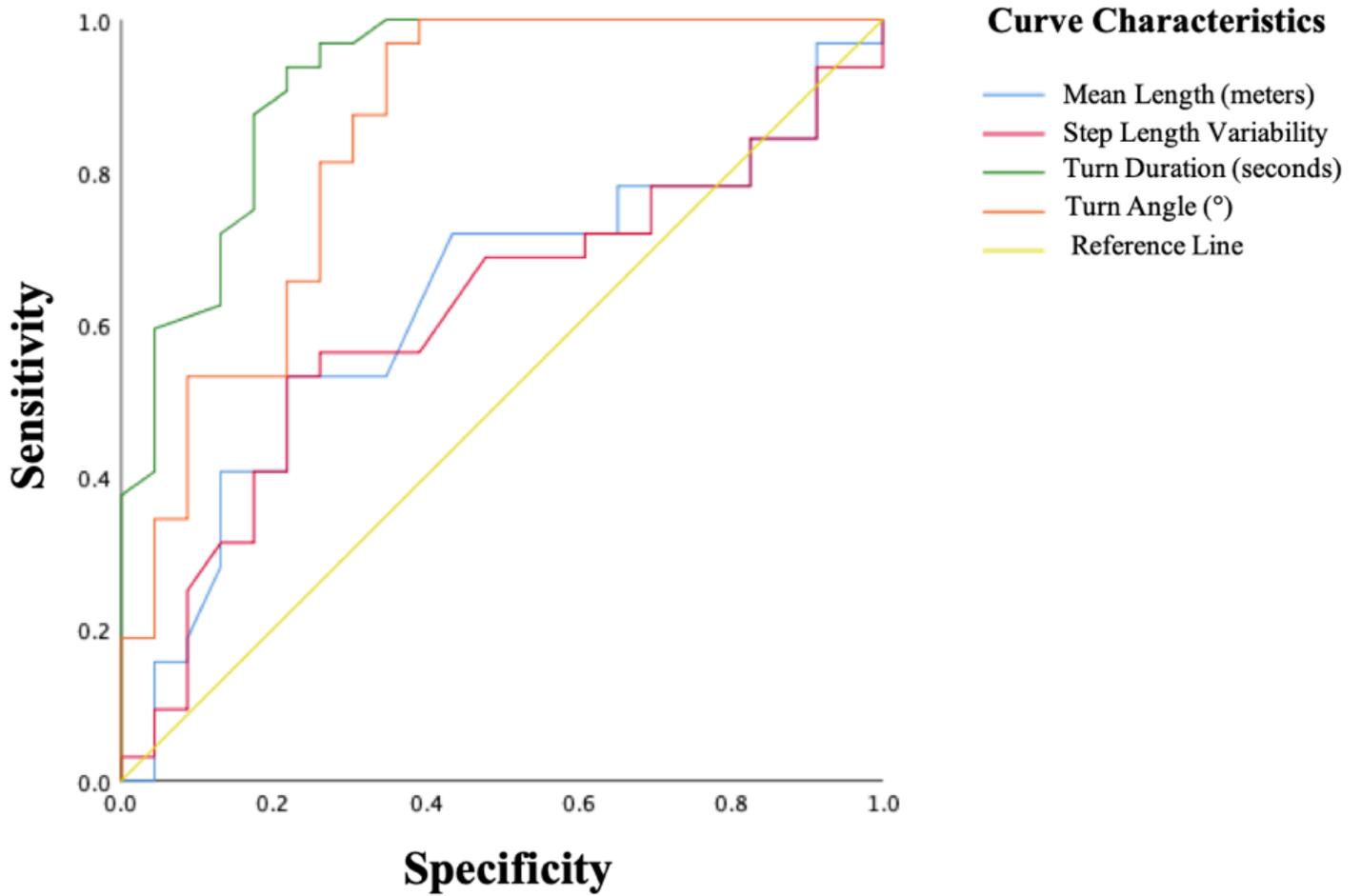


Figure 1

Receiver operator character (ROC) analysis for the top two turning and gait characteristics. Which distinguish chronic MTBI from controls