Analysis of free-living mobility in people with mild traumatic brain injury and healthy controls: Quality over Quantity

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Abstract

Balance and mobility issues are common non-resolving symptoms following mild traumatic brain injury (mTBI). Current approaches for evaluating balance and mobility following an mTBI can be subjective and sub-optimal as they may not be sensitive to subtle deficits, particularly in those with chronic mTBI. Wearable inertial measurement units (IMU) allow objective quantification of continuous mobility outcomes in natural free-living environments. This study aimed to explore free-living mobility (physical activity and turning) of healthy and chronic mild traumatic brain injury (mTBI) participants using a single IMU.

Free-living mobility was examined in twenty-three healthy control (48.56±23.07years) and twenty-nine symptomatic mTBI (40.2±12.1years) participants (average 419days post-injury, persistent balance complaints) over one week, using a single IMU placed at the waist. Free-living mobility was characterized in terms of Macro (physical activity volume, pattern and variability) and Micro-level (discrete measures of turning) features.

Macro-level outcomes showed those with chronic mTBI had similar quantities of mobility compared to controls. Micro-level outcomes within walking bouts showed that chronic mTBI participants had impaired quality of mobility. Specifically, people with chronic mTBI made larger turns, had longer turning durations, slower average and peak velocities (all $p<.001$) and greater turn variability compared to controls. Results highlighted that the quality, rather than quantity of mobility differentiated chronic mTBI from controls.

Our findings support the use of free-living IMU continuous monitoring to enhance understanding of specific chronic mTBI-related mobility deficits. Future work is required to develop an optimal battery of free-living measures across the mTBI spectrum to aid application within clinical practice.

KEYWORDS: mTBI, concussion, wearable sensor, free-living, turning, physical activity

Introduction

An array of symptoms accompany acute mild Traumatic Brain Injury (mTBI), including subtle motor, cognitive and sensory abnormalities (vestibular, visual and somatosensory).[1-5] These deficits persist in a majority of adults with mTBI, who experience symptoms >3 months following initial injury[6] that directly impact quality of life.[7-9] Sub-clinical, non-resolving problems with motor functions, such as balance[10] or gait,[11] are common following an mTBI, relate to cognitive[12] and sensory[13] deficits, and have implications for limiting everyday function. Relationships stem from the requirement of sensory and cognitive processing for safe and effective mobility, especially for complex motor tasks such as turning that require control of dynamic balance and sequential, whole-body coordination. Previous work has shown that up to 81% of people with acute mTBI report some form of imbalance and up to 31% of people with mTBI will have prolonged issues.[14-17] However, balance and mobility following mTBI have been traditionally assessed within clinic using subjective clinical rating scales (e.g. Balance Error Scoring System (BESS) etc.) that may not be sensitive to subtle deficits or representative of functional impairment within daily living that objective quantitative measurements could provide[18].

In recent years there has been an emphasis on using objective and instrumented measures of gait and balance. A trend in research has demonstrated that objective measurement of balance and gait, using force plates, 3-dimensional motion capture systems, walking mats, and wearable sensors provide greater sensitivity to mTBI-related deficits compared to standard clinical assessments.[19, 20] Similarly, recent studies have developed techniques to study gait and balance in animal models of mTBI, such as video analysis, CatWalk XT or DigiGait gait analysis systems that are usually conducted at 1, 4 and >24hr after injury.[21-24] Such studies provide a one-off 'snapshot' of performance, and have demonstrated deficits in balance and gait measures (particularly slower walking speed,[25] altered gait termination strategies[26] and larger medio-lateral sway[27, 28]) with mTBI, which occur even when individuals appear to be clinically 'normal' or ‘recovered’. Nonetheless, studies in this area have shown mixed results,[11] and the majority of laboratory assessments have been limited to assessing standing balance or measuring gait along straight pathways. Many previous studies also only assessed a limited number of gait or balance measures (i.e. only gait speed),[11] which limits understanding of subtle but important deficits in chronic mTBI. Usual daily activities can involve more complex and dynamic movements, suggesting previous laboratory-based research may not be capturing true deficits. Indeed, previous work in healthy adults has shown that up to 45% of daily steps are not straight ahead and that people perform up to 1000 turns per day.[29, 30] Furthermore, previous studies have demonstrated that turning is impaired in mTBI, with greater variability in turn onset across body segments exists even after medical staff cleared subjects to return-to-play.[31] There is also less kinematic whole-body roll when turning that can take up to one year to recover.[32] These measures of turning may not be detectable by clinical assessment. Similarly, our recent work has demonstrated impaired turning within a laboratory setting (45°, 90°, 135°) in patients with chronic (symptoms >3months following initial injury) mTBI compared with controls.[33] Specifically, deficits in turn velocity and peak velocity timings were prevalent in those with chronic mTBI. Results from these controlled laboratory assessments are very informative and point toward defined deficits in turning. Yet, the laboratory-based nature may not capture true deficit in everyday function. Comparatively, free-living assessment over longer periods of time may provide greater understanding of mobility deficits in those with mTBI as well as the functional impact on daily living.

With the advancement of affordable wearable inertial sensor technology (e.g. accelerometers, gyroscopes, magnetometers), it is now possible to assess a range of objective balance and gait outcomes within natural free-living environments in both human[34, 35] and animal models of mTBI.[36, 37] Continuous monitoring of activity during unsupervised activities (free-living) may provide more sensitive measures of mobility impairment following an mTBI than laboratory-instrumented or subjective clinic-based assessment. Free-living continuous monitoring captures mobility in a wide framework of contexts, from macro-level characteristics (e.g. pattern, volume and variability of activity bouts; or quantity outcomes) to more subtle micro-level characteristics (e.g. spatial-temporal gait or turning characteristics; or quality outcomes).[38, 39] In this context, wearable sensors have been shown to be a valid tool to assess physical activity and turning in free-living.[29] However, only two previous studies have reported selective macro characteristics (i.e. only steps per day) within free-living environments in children with acute mTBI using inertial sensors.[40, 41] Both studies reported that this approach held promise in discriminating acute mTBI from controls using such outcomes. To date however, no study has comprehensively assessed macro characteristics in those with chronic mTBI, and, to our knowledge, no studies have examined free-living micro characteristics of turning in patients with mTBI, regardless of chronicity. Free-living outcomes may be particularly useful in the assessment of people with chronic mTBI, as these individuals typically have persistent symptoms that do not relate to outcomes from traditional balance of gait assessments.[42, 43] Assessing macro-level (e.g. physical activity measures) and micro-level (e.g. turning measures) mobility characteristics in those with chronic mTBI and controls may improve our understanding of how mobility is impaired in mTBI within free-living conditions. This information may provide insight into whether free-living home monitoring assessments can help to objectively discriminate between mTBI and healthy persons, and could highlight specific targets for individually tailored rehabilitation or interventions.

The aim of this study was to describe free-living mobility in chronic mTBI compared with controls, which incorporated both macro and micro-level mobility features. Specifically, we compared traditional measures of physical activity level and novel turning measures in people with chronic mTBI and healthy controls. We hypothesized that free-living turning rather than general physical activity would differentiate those with chronic mTBI from healthy controls.

Methods

Participants

Free-living mobility was examined in 23 healthy control subjects and 29 symptomatic people with chronic complaints of imbalance following an mTBI. Participants were measured over one week using one inertial measurement unit (IMU) attached to a waist worn belt. The belt was worn throughout the day for a minimum of 5 hours per day. Detailed study methodology and protocol has been published elsewhere,[44] but we provide a brief outline below.

Participants were recruited as part of a larger study (detailed elsewhere; see [44]), through posters in athletic facilities, physical therapy clinics, hospitals, concussion clinics, community notice boards and cafes in and around the Portland, Oregon metropolitan area. Research assistants screened subjects over the phone according to the inclusion and exclusion criteria prior to enrollment. Participants were included if they: (1) had a diagnosis of mTBI based upon VHA/DoD criteria[45] who were >3 months post mTBI with persistent balance complaints for the mTBI group, or had no history of brain injury in the past year for the control group, (2) had no cognitive deficits as determined by the Short Blessed Test (score ≤8), and (3) were between the ages of 18 and 60 years. Exclusion criteria consisted of musculoskeletal injury in the previous year that could have seriously impacted gait or balance; current moderate or severe substance abuse; any peripheral vestibular or oculomotor pathology from before their reported mTBI; or refusal to abstain from medications that could impact their mobility for the duration of testing. Participants were asked to abstain from medications that could impact their mobility starting 24 hours prior to their first testing date. Prohibited medications included sedatives, benzodiazepines, narcotics pain medications and alcohol. All recruitment procedures were approved by the Oregon Health & Science University (OHSU) and Veterans Affairs Portland Health Care System (VAPORHCS) joint institutional review board and participants provided written informed consent prior to commencing the study.

Demographic and clinical measures

Demographic characteristics of age, gender, height, weight, and date of injury (for mTBI group) were obtained. Clinical symptoms were recorded by the mTBI participants using the Neurobehavioral Symptom Inventory (NSI), with a high score indicative of worse symptoms.[46]

Data Analysis

Participants wore a small, lightweight IMU (128Hz, Opal, APDM Inc., Portland, OR, USA) attached to a belt on their waist, which included a triaxial accelerometer, gyroscope and magnetometer. Data were recorded and stored in the secure digital card of the IMU, and were later transferred to a laptop for processing and analysis. All data analysis was conducted using a validated custom-made MATLAB (R2017b, The MathWorks Inc., Natick, Massachusetts, USA) algorithm for the assessment of free-living turns and physical activity in neurological conditions, which has been detailed elsewhere.[29, 47] A brief overview of the algorithm is described below.

Data length was first checked to ensure correct number of days. Participants were asked to wear the monitor for a period of 7 days, however several participants wore it for longer periods (up to 12 days) and several control (n=2) and mTBI (n=2) participants were unable to comply with the 7 day request. Therefore, a minimum of 3 days were required for data processing and analysis, in line with our previous validation studies.[29, 47-49] Each day was also required to contain a minimum of 5 hours of continuous recording in order to be processed, with days <5hours excluded from further analysis (Number of days worn; mTBI = 7.41±2.29, control = 6.39±1.67).

A previously validated algorithm identified periods of walking activities within free-living and calculated the physical activity and turning metrics during each hour of the day, with precise methods detailed elsewhere.[29, 47, 50] In brief, periods of walking (steps) were detected first, due to the use of a single IMU this involved implementation of a previously reported continuous wavelet transform algorithm.[51, 52] This extracted initial foot contact and final foot contact,[53] within a predefined timed period from a previous step of 0.25-2.25secs,[54] from the vertical tri-axial accelerations,[51, 52] with an individual walking period of >10secs defined as a "gait bout" (bouts below this duration were ignored). Next, turns were detected within these gait bouts. Turning events during gait were detected using the horizontal (yaw) rotational rate of the waist sensor (>15°/sec represented a turn, with the start and end of turns set to point where rate dropped below 5°/sec), with a minimum of 45° trunk rotation around the vertical plane and duration of 0.5-10secs required for classification. Integration of the angular rate of the waist sensor about the vertical axis was used to define relative turn angles.

Macro and Micro-level outcomes

Macro and micro-level mobility outcomes were instrumented measurements of physical activity and turning across the week of free-living monitoring. Specific metrics are detailed below;

Macro-level physical activity characteristics included walking bout duration (seconds), coefficient of variation (CV) of bout duration, total number of steps per daily bouts (i.e. accumulation of steps within gait bouts >10s across a day) and active rate (i.e. percentage of time walking or turning compared with full time of monitoring during the day).

Micro-level turning characteristics included number of turns per hour, average turn angle (°), peak turn velocity (°/sec), average turn velocity (°/sec), turn duration (seconds) and CV of these measures.

Statistical Analysis

Data were analyzed in SPSS (v23, IBM). Normality of data was determined with Shapiro-Wilk tests and parametric analysis was used throughout, unless otherwise stated. Descriptive statistics (Mean and standard deviation, or equivalent) were calculated for demographic characteristics and for daily physical activity and free-living turning metrics. Independent t-tests and Chi-squared analysis compared demographic outcomes between groups. Separate analysis of covariance

(ANCOVA) models were used to compare the turning and physical activity outcomes between the chronic mTBI and control groups, while controlling for age and gender. Due to the exploratory nature of the study we did not control for multiple comparisons and statistical tests were two-tailed with a $p<0.05$ considered significant.

Results

Participants

Participant demographic information is included in Table 1. The chronic mTBI and control groups were well matched for age (p=0.120) and gender (p=.447). NSI total score was much higher in our mTBI group compared to previously reported normative data,[55] which indicated that our mTBI cohort were symptomatic.

Free-living turns are more sensitive to mTBI than physical activity measures

The physical activity and turning measures for chronic mTBI and control participants are provided in Table 2. Each of the Micro-level turning measures were significantly different between the mTBI and healthy controls (all p<0.05). In contrast, none of the Macro-level physical activity measures were significantly different between groups (p = 0.087 to 0.962).

Discussion

To the best of our knowledge, this is the first study to quantify a relatively comprehensive framework of free-living mobility in symptomatic individuals with chronic mTBI and healthy controls. Specifically, we examined traditional macro (physical activity) and novel micro-level (turning) mobility measures over one week with a waist worn IMU. Our findings show that micro-level measures of free-living turning rather than macro-level physical activity measures were different between people with chronic mTBI and healthy controls. These findings highlight that micro-level mobility characteristics can provide a more subtle understanding of mobility deficits in mTBI. Furthermore, measuring these characteristics may help to guide tailored intervention strategies.

Macro-level Physical Activity Characteristics

Physical problems in acute mTBI, such as mobility issues, are not well understood. Mobility deficits may occur in the acute stages of mTBI, which has been shown through instrumented gait and balance assessments in animal[21, 22] and human[27, 32, 56, 57] models, but evidence is unclear whether deficits persist into the chronic phase.[5, 22] Clinicians can have difficultly detecting and diagnosing the subtle changes that can occur,[58, 59] particularly in patients with chronic self-reported symptoms due to development of neural compensation for pro-longed deficits.[60] Previous studies of post-mTBI physical activity levels have primarily been limited to examination through subjective self-reported questionnaire-based assessments.[61, 62] These studies have reported weak or inconsistent relationships between physical activity levels and mTBI, but generally physical activity levels (specifically steps per day) are thought to be impacted by an mTBI and may relate to specific symptoms (e.g. neurocognitive performance).[62] Our objective measurement of physical activity is likely more sensitive to actual free-living activity levels than subjective questionnaire-based measurement, as subjective rating is limited by patient understanding of the impact of concussion on functional mobility.[63-65] For example, some patients with mTBI may have an inability to recognize and to accurately report mobility deficits.

More recently technological progression has been made so that wearable IMU technology (i.e. accelerometers, gyroscopes etc.) can be implemented within an mTBI population to objectively quantify physical activity within a free-living environment,[66] which has been conducted in several pediatric pilot studies of acute mTBI[40, 41] and one animal model (piglets) TBI study.[36] In contrast to previous subjective studies, the current study has shown that IMU quantified physical activity metrics (Table 2) were not different between people with chronic mTBI and controls. Both cohorts (mTBI and controls) in our study made around 5,000-6,000 steps per day on average, consistent with typical of daily activity where <5,000 steps per day indicates sedentary behavior.[67] Findings are similar to previous acute mTBI research[68] and levels reported in those with more severe TBI.[69] These previous studies have shown that despite being lower than the recommended 10,000 steps per day,[67] IMU quantified physical activity (i.e. step count) levels are not different in people with chronic mTBI. Macro-level mobility measures may therefore not be useful in differentiating people with chronic mTBI from controls. However, objective measurement of free-living mobility could augment subjective questionnaire-based assessments in the clinic, as these may not truly represent actual functional performance. The prescription of a week of continuous monitoring in people following an mTBI (any stage) may aid in clinical decisions and intervention selection.

Micro-level Turning Characteristics

In line with our hypothesis, several micro-level features of turning performance (i.e. turn angle, duration, peak and average velocity) were impaired in people with chronic mTBI compared with controls within free-living conditions. This evidence furthers previous laboratory-based turning research in acute/subacute sports-related concussion[31] and chronic mTBI,[33] which have shown that turning performance was deficient and able to differentiate mTBI from controls. Deficient quality of turning, but not quantity of turning or physical activity measures, suggests that people with chronic mTBI can maintain a similar amount of turning or walking to controls but subtle mTBI-related deficits alter how they turn. Turning requires a change in direction that occurs rapidly with coordinated segmental reorientation of the head, trunk and pelvis, which may be more susceptible to mTBI impairments compared macro-level activity.[70] For example, turns involve greater inter-limb and segmental co-ordination than straight walking, as well as precise integration of sensory information and more postural and gait coupling. Free-living turn angle, velocity, duration and variability were altered with chronic mTBI and differentiated those with chronic mTBI from controls, which may indicate a lack of dynamic balance control that is necessary to modulate movement in response to environmental changes[25] and provide useful targets for rehabilitation interventions. Furthermore, precise measures of mobility that can objectively characterize subtle movements could therefore provide clinicians with a simple assessment tool for chronic mTBI deficits[27]. Monitoring of mobility with small, body-worn IMUs allows for the evaluation of subtle changes in movement (i.e. turns) following injury and could be used for assessments following rehabilitation or over the course of a graded return-to-play (or work/duty/school),[34] with functional implications of real-world assessment.

Interestingly, despite poor quality of turning, people with chronic mTBI made more turns per hour than controls, the intrinsic meaning of this difference remains unclear. A greater number of turns may be a compensatory strategy to account for issues with turn magnitude or speed deficits; however, it could also be due to impaired dynamic balance control leading to increased number of turns throughout the day (i.e. inability to control subtle movements). Unfortunately, no previous mTBI studies exist for direct comparison of continuous turning findings. However, several previous studies have shown non-significantly increased number of turns with Parkinson's disease[47] and those who report freezing of gait,[50] which highlights that increased quantity of turns may relate to neurological impairment. Further work is required to understand this finding.

Study strengths and limitations

A major strength of the current study is the use of a single IMU for the objective quantification of mobility within those with mTBI. In the future, development of user-friendly software could enable implementation of this technology by clinicians within a variety of locations (i.e. clinic, pitch-side, home etc.) and could monitor activity over a pro-longed period to provide detailed analysis of functional performance. The application of the IMU is simple and took less than 5-10mins to explain to patients how to use/charge device. This approach could be a cost-effective means of clinical assessment of mobility (i.e. reduces the number of clinic visits). However, before wearable IMU technology can be adopted within regular clinical practice it must be robustly evaluated for clinical usefulness, with scientifically validated data processing and analysis methodologies.[35, 71]

Device application in clinic is currently hindered by the lack of consistency in IMU data processing algorithms, validation protocols, sensor choice and positioning, as well as application to specific pathologies,[72] which all need to be addressed before clinical adoption.

There are several limitations to note. Firstly, due to the exploratory nature of the study, we reported a limited assessment battery for mTBI-related symptoms (i.e. only the NSI questionnaire) and did not assess controls for these features. Secondly, we did not record the occupation, current work status or weekday/weekend IMU use of the controls or chronic mTBI groups, therefore data may be influenced by sedentary or physically active occupations. Thirdly, we only compared 'macro-level' gait metrics (e.g. steps per day) with more subtle 'micro-level' turning outcomes (e.g. turn velocity, duration etc.). Future studies could compare turning to specific free-living 'micro-level' gait characteristics (e.g. spatial-temporal gait measures, gait stability, asymmetry or adaptability measures) using validated algorithms for single waist-mounted IMU analysis (for example; [52]) to uncover which is more sensitive to chronic mTBI deficits. Finally, we had a relatively small number of participants that limited power for further analysis of relationship between free-living outcomes and other features (e.g. symptoms, subtle cognitive or sensory impairment etc.). Future studies should address these limitations and examine findings within a larger cohort and within different concussion stages (e.g. acute, sub-acute, and chronic) to further inform the specific deficits involved.

Conclusions

The present study has demonstrated that a single inertial sensor can be used to obtain continuous measures of mobility in free-living environments in symptomatic people following a chronic mTBI. Specifically, free-living micro-level turning characteristics rather than general macro-level physical activity measures were impaired in symptomatic people with chronic mTBI compared with healthy controls. Therefore, objective quantification of mobility within free-living using unobtrusive technology has the potential to extend clinical assessment of chronic mTBI, and provides a useful and realistic measure of patient function within their daily lives.

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Conflicts of Interest

The authors declare no conflict of interest.

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Table 1 - Demographic and clinical outcomes

	Chronic mTBI (n=29)	Control (n=23)	*p*
Demographics			
Age	40.70 (12.10)	48.56 (23.07)	.120
Gender	M (6) / F (23)	M (6) / F (17)	.447
Height (cm)	144.64 (46.74)	168.99 (11.48)	.938
Weight (kgs)	76.53 (19.78)	68.03 (16.25)	.250
Days since injury[a]	419 (212, 841)	-	-
NSI – total score	35.45 (14.14)	-	-

[Mean and standard deviation reported unless otherwise stated. [a]Median and Inter-quartile Range. mTBI = mild traumatic brain injury]

Table 2 - Turning and Physical Activity Measures in mTBI and Controls

	Chronic mTBI (n=29)	Controls (n=23)		
	Mean (SD)	**Mean (SD)**	***F***	***p***
Macro-level Physical Activity				
No. Bouts per hour (n)	16 (5)	15 (5)	0.89	.352
Bout Duration (sec)	48.41 (17.58)	44.89 (17.79)	0.52	.476
Bout Duration CV (sec)	0.83 (0.12)	0.82 (0.12)	0.00	.962
Average Steps per Bout (n)	48 (24)	46 (32)	0.08	.786
Total Steps per Daily Bouts (n)	5863 (2606)	5034 (1997)	1.13	.294
Active Rate (%)	19.53 (7.34)	16.44 (4.62)	3.05	.087
Micro-level Turning				
No. Turns per hour (n/hr)	85 (33)	60 (24)	7.46	**.009***
Angle (°)	97.79 (3.63)	82.02 (12.62)	60.57	**<.001***
Angle CV (°)	0.48 (0.02)	0.39 (0.09)	41.89	**<.001***
Duration (sec)	1.73 (0.11)	1.14 (0.39)	75.95	**<.001***
Duration CV (sec)	0.42 (0.02)	0.36 (0.07)	15.80	**<.001***
Peak Velocity (°/sec)	97.22 (7.92)	149.84 (40.09)	58.26	**<.001***
Peak Velocity CV (°/sec)	0.36 (0.03)	0.32 (0.03)	16.60	**<.001***
Average Velocity (°/sec)	48.94 (3.68)	73.45 (18.63)	57.35	**<.001***
Average Velocity CV (°/sec)	0.34 (0.02)	0.32 (0.04)	4.90	**.032***

[ANCOVA results controlling for age and gender]