Gait Performance in People with Symptomatic, Chronic Mild Traumatic Brain Injury

Douglas N. Martini[1,2]*, Lucy Parrington[1,2], Samuel Stuart[1,2,3], Peter C. Fino[4], Laurie A. King[1,2]

[1] *Department of Neurology, Oregon Health & Science University, Portland, OR, USA*

[2] *Veterans Affairs Portland Healthcare System, Portland, OR, USA*

[3] *Department of Sport, Exercise and Rehabilitation, Northumbria University, Newcastle upon Tyne, UK*

[4]*Department of Health, Kinesiology, and Recreation, University of Utah, Salt Lake City, UT, USA*

Douglas N Martini, PhD; Department of Neurology, Oregon Health & Science University, 3181 Sam Jackson Park Rd, L105, Portland, OR 97239
P: 503-418-2601 E: martidou@ohsu.edu

Lucy Parrington, PhD; Department of Neurology, Oregon Health & Science University, 3181 Sam Jackson Park Rd, L105, Portland, OR 97239
P: 503-418-2601 E: parringt@ohsu.edu

Samuel Stuart, PhD; Department of Sport, Exercise and Rehabilitation Northumbria University Northumberland Building (318) Newcastle upon Tyne, NE1 8ST, United Kingdom
P: +44 (0) 191 227 3343 E: sam.stuart@northumbria.ac.uk

Peter C Fino, PhD; Department of Health, Kinesiology, and Recreation University of Utah, 250 S 1850 E Salt Lake City, UT, 84112
P: 801-213-1363 E: peter.fino@utah.edu

Laurie A King, PhD, PT; Department of Neurology, Oregon Health & Science University, 3181 Sam Jackson Park Rd, L105, Portland, OR 97239
P: 503-418-2602 E: kingla@ohsu.edu

Running Title: Gait in Symptomatic Chronic mTBI

***Corresponding Author:**
Douglas N Martini, PhD
Post-Doctoral Research Fellow
Department of Neurology
Oregon Health and Science University
3181 SW Sam Jackson Park Rd, L105,
Portland, Oregon, USA, 97239
P: 503-418-2601
E: martidou@ohsu.edu

Abstract

There is a dearth of knowledge about how symptom severity affects gait in the chronic (>3 months) mild traumatic brain injury (mTBI) population despite up to 53% of people reporting persisting symptoms following mTBI. The purpose of this investigation was to determine if gait is affected in a symptomatic, chronic mTBI group and to assess the relationship between gait performance and symptom severity on the Neurobehavioral Symptom Inventory (NSI). Gait was assessed under single- and dual-task conditions using five inertial sensors in 57 control subjects and 65 people with chronic mTBI (1.1 year from mTBI). The single- and dual-task gait domains of Pace, Rhythm, Variability, and Turning were calculated from individual gait characteristics. Dual-task cost (DTC) was calculated for each domain. The mTBI group walked (domain z-score mean difference: single-task = 0.70; dual-task = 0.71) and turned (z-score mean difference: single-task = 0.69; dual-task = 0.70) slower ($p<0.001$) under both gait conditions, with less rhythm under dual-task gait (z-score difference = 0.21, $p=0.001$). DTC was not different between groups. Higher NSI somatic sub-score was related to higher single- and dual-task gait variability as well as slower dual-task pace and turning ($p<0.01$). People with chronic mTBI and persistent symptoms exhibited altered gait, particularly under dual-task, and worse gait performance related to greater symptom severity. Future gait research in chronic mTBI should assess the possible underlying physiological mechanisms for persistent symptoms and gait deficits.

Key Words: concussion, long-term, persisting symptoms, gait domains, wearable sensors

Introduction

Complete recovery following a mild traumatic brain injury (mTBI) is believed to occur within one month, though possibly quicker in athlete populations.[1, 2] Yet, recent evidence suggests that up to 53% of people still report symptoms up to one-year post-mTBI, and two separate investigations have observed symptomatic complaints four and five years post mTBI.[3-5] Unfortunately these persistent symptoms can affect quality of life.[4-7] In order to better care for mTBI populations with persisting symptoms, a deeper understanding of how symptoms relates to functional outcomes relevant for activities of daily living is needed. Understanding this relationship would help bridge the gap between patient reported outcomes and objective measures of daily activity-related functional performance.

Gait performance is an important functional measure and impaired gait occurs in the acute phase of mTBI,[8-10] as well as some reports that subtle deficits may persist for years after an mTBI.[11] However, gait deficits are inconsistent across reports including some studies that report no lasting gait deficits at all. Across nine publications that investigated gait in people with chronic mTBI (>3 months post mTBI), only three reported persisting symptoms of any type in the chronic mTBI group.[12-14] Further, only four reported slowed gait, and only one of these reported deficits in other aspects of gait.[14-20] Beyond possible influences of population (e.g. athlete, non-athlete, and age) and mechanism of mTBI (e.g. blunt force or blast), the conflicting evidence of gait dysfunction in this chronic population may be attributable to reporting of different gait metrics and different testing paradigms across publications. For example, a majority of studies primarily report gait speed under single-task gait,[11, 18] while recent work suggests that there are multiple and independent domains of gait (e.g. pace and variability).[21, 22]

Recently, a statistical approach using principal component analysis has been proposed to group individual gait characteristics into independent domains.[21, 22] This approach provides an opportunity to

measure all components of gait, while reducing the number of metrics analyzed. Such gait models have been applied to other neurological populations including Parkinson's disease, elderly and, more recently, mTBI.[21-25] Our recent publication in the mTBI population, identified four independent gait domains (Variability, Rhythm, Pace, and Turning).[25] These four domains provide a more complete characterization of gait performance, uncovering possible gait deficits potentially overlooked in previous investigations. As noted, the Pace domain is most often reported in the chronic mTBI gait literature. However, Rhythm, Variability, and Turning may be related to more real-world gait performance and could be related to discrete cortical areas independent from the Pace domain.[22]

Most studies assess gait using gait speed; a simple protocol that measures gait during straight-ahead walking.[17, 26] Other studies use increasing gait complexity (e.g. dual-task, obstacle avoidance, turning course) in an effort to uncover subtle gait dysfunction.[27] This distinction in varying protocols is important since complex gait involves both motor and cognitive input.[28] Assessing a dual-task gait condition with a secondary task that requires the allocation of attention away from gait performance is thought to simulate "real world" gait demands.[29] Further, a recent focus on measuring turning as a separate component of gait has revealed deficits in people with mTBI. Specifically, two recent publications report that individuals with chronic mTBI exhibit slower and more variable turns compared to otherwise healthy individuals,[30, 31] both in the clinical assessment and in a home setting. Aside from characterizing multiple components of gait and assessing gait under complex conditions, accounting for patient reported outcomes could help mitigate the heterogeneity of reported gait dysfunction across the chronic mTBI population.

An established body of literature links gait dysfunction to depression, cognitive impairment and motor disorders.[24, 32, 33] For example, depression relates to slowed gait and increased risk of falls,[34-36] cognitive

impairment relates to increased gait variability and increased gait decline,[37, 38] and motor disorders relates to decreased variability, speed, turning and rhythm.[24, 39, 40] While people with mTBI report symptoms that fall under these categories, other symptoms common to mTBI, such as headaches, visual disturbances, and impaired sleep might relate to gait dysfunction as well. Currently, however, there is a lack of knowledge regarding the relationship between mTBI-related symptoms and gait dysfunction in the chronic mTBI population.

The purpose of this investigation was to determine if 1) gait domains are different between people with and without chronic mTBI, 2) adding a dual task exacerbates these differences in gait across domains, and 3) self-reported symptom severity scores are related to gait performance across domains. We hypothesized that the people with chronic mTBI would exhibit dysfunction across the four gait domains, represented by slower pace, less rhythm, more variability, and slower turning than the control group and that worse symptom reporting would be associated with worse gait performance (e.g. slower pace, greater variability, slower turns), particularly under the dual-task gait condition.

Methods

The Institutional Review Board approved this study and all participants signed an informed consent prior to participation. Individuals with and without a history of mTBI were screened for participation eligibility. All data were collected as part of a larger clinical trial (NCT02748109) aimed at characterizing the differences between chronic mTBI and healthy matched controls, and evaluating the effectiveness of vestibular rehabilitation. Description of the trial protocol, and the inclusion and exclusion criteria have been previously described.[41] Briefly, inclusion criteria for the mTBI group were: diagnosis of mTBI based upon Veteran Health Affairs/Department of Defense criteria, with symptoms persisting >3 months post-mTBI;[42] between 21–60 years old. Inclusion criteria for the control group were: between 21–60 years old

and no self-reported history of mTBI or brain injury. Exclusion criteria were: any other injury, medical, substance or neurological illness that could potentially explain balance deficits (e.g., central nervous system disease, stroke, lower extremity amputation); significant hearing loss; inability to follow directions; unable to abstain from medications that might impair balance for 24 hours prior to testing.

Gait Assessment

Gait was assessed using inertial sensors (Opals, APDM Inc.), which have been shown to have good validity and reliability for gait characterization.[43, 44] Sensors were placed on each foot, the forehead, lumbar vertebrae, and over the sternum. Participants were instructed to walk at a comfortable, self-selected pace during single- and dual-task conditions. Each walk was eight laps of a 13-meter path (208 m total); requiring 180 degree turns at the ends of the marked path. The secondary task was an auditory Stroop test.[45] Wearing headphones, participants listened to auditory stimuli consisting of the words "high" and "low", which were randomly paired congruently or incongruently with the pitch (i.e. high and low) of the voice, and delivered at 2.25-second intervals. Participants were instructed to respond saying the pitch of the word as quickly as they could. The outcome variable for the auditory Stroop test was accuracy (percent correct).

Symptom Assessment

Each participant completed the Neurobehavioral Symptom Inventory (NSI) questionnaire,[46, 47] which is established as a valid and reliable symptom assessment.[48] The NSI consists of 22 items, each rated on a five-point Likert scale, with a higher score indicating more severe symptoms for this scale and a maximum score of 88. The participants were asked to rate each item based on how that symptom disturbed them over the preceding two weeks. The original categorization of the NSI items describes four sub-categories (affective, cognitive, somatic, and sensory), however, more recent descriptions

reduced these to three sub-categories (affective, cognitive, and somatic/sensory) by combining the somatic and sensory sub-categories from the original.[46, 48, 49]

Statistical Analyses

Data were inspected for normality using histograms and the Kolmogorov-Smirnov test of normality. All data were normally distributed. Independent-samples t-tests were used to compare demographic information between the groups. Levene's test for equality of variance was followed as needed. Chi-Squared test was used to assess the gender differences between the groups. Comprehensive gait measures were divided into four domains based on the previously described model;[25] Pace, Rhythm, Variability, and Turning. Domain scores were calculated by averaging the Z-scores for each gait variable.[25] Z-scores were multiplied by -1 to reverse scaling if needed for consistent sign in domain score calculations. Dual-task cost was calculated (dual-task cost = 100*[dual-task – single-task]/single-task) for each participant for each gait domain, individual gait characteristic, and the accuracy for the secondary task. The dual-task cost direction (e.g. positive or negative) remained unaltered when calculating group means for dual-task cost. A series of one-way ANOVAs assessed the gait domains and secondary task performance for between-group differences. Cohen's *d* effect sizes were calculated to characterize the magnitude of the group effect on gait and secondary task performance.[50] Effect sizes were interpreted as weak (<0.50), moderate (0.50-0.79), or strong (≥0.80) as previously described.[50] Pearson's correlations assessed the relationships between symptom scores and both single-task and dual-task gait performance within the mTBI group only. Alpha was set *a priori* to 0.05, but Bonferroni correction was applied for the gait domain (four single-task, four dual-task, and four dual-task cost) and secondary task performance group comparisons (one single-task, one dual-task, and one dual-task cost; total of 15), therefore alpha was set to 0.003 for these group analyses.

Results

A total of 192 individuals were screened for participation. Of these people, 65 people with chronic mTBI and 57 matched controls participated in this study. **Table 1** provides the group demographics and NSI scores for both groups. The mTBI group reported a significantly higher total score for the NSI ($t_{(70.86)}$ = 17.88; $p < 0.001$), as well as for each subcategory (somatic: $t_{(67.63)} = 15.95$; $p < 0.001$; affective: $t_{(80.11)} = 14.89$; $p < 0.001$; cognitive: $t_{(74.83)} = 14.96$; $p < 0.001$;).

Gait Performance

Group means and standard deviations for the gait domains, as well as the F statistic and Cohen's d values are provided in **Table 2**. Under single-task gait, the mTBI group only exhibited slower Pace ($p < 0.001$) and Turning ($p < 0.001$) compared to the control group. Under dual-task gait, Pace ($p < 0.001$), Turning ($p < 0.001$), and Rhythm ($p = 0.001$) were slower in the mTBI compared to the control group. We observed no group differences for any of the dual-task cost on gait domains. The unstandardized, individual gait characteristics are in **Table 3**.

Correlation analyses between symptom scores and the gait domains are presented in **Figure 1**. The NSI total score was significantly related to gait Variability in both the single- and dual-task conditions. The NSI somatic sub-score was significantly related to gait Variability and Turning in both the single- and dual-task conditions. The NSI cognitive sub-category score was related to gait Variability under single-task (Pearson's r = 0.43; $p = 0.001$) and dual-task (Pearson's r = 0.40; $p = 0.002$) conditions, while the NSI affective sub-category score was only related to gait Variability under single-task (Pearson's r = 0.37; $p = 0.005$). Neither the NSI total symptom score nor any sub-category score related to any of the dual-task costs on gait domains.

Auditory Stroop Performance

There were no group differences for the auditory Stroop accuracy for the single-task (seated) or dual-task (walking) conditions, nor for the dual-task cost on Stroop Accuracy (**Table 2**).

Discussion

We assessed gait performance in people with persistent symptoms in the chronic phase of mTBI and healthy controls, using both a single- and dual-task gait paradigm. We report that people with chronic mTBI have deficits across multiple gait domains including slower Pace and Turning under both single-task and dual-task gait conditions, as well as less Rhythm under dual-task gait compared to healthy controls. Further, more severe symptoms related to increased gait Variability, as well as decreased Pace and Turning in the chronic mTBI group.

The altered gait domains (reduced Pace, Turning, and Rhythm under dual-task gait) in this chronic mTBI cohort expands the previous results from the literature including our previous work on two subsets of this chronic mTBI cohort.[30, 31] Specifically a small subset of people who performed a prescribed turning course that required participants to make multiple turns ranging from 45° to 135°, showed increased segmental variability during turns.[30] The second subset had their turning characteristics assessed in their home, over one week, and with reportedly abnormal turns.[31] These results, combined with our current results, suggest a preliminary pattern of turning deficits in people with chronic mTBI and persistent symptoms. Data from turns during gait provide greater insight into quality of performance for activities of daily living since turning can occur over 750 times per day in the home.[51] In fact, turning is thought to be more cognitively demanding than straight walking,[52, 53] which aligns with our results. Turning was significantly different between groups under both single- and dual-task gait, suggesting that single-task turning during gait may require enough executive function to be considered a cognitively demanding

task. In a laboratory based setting, we also observed gait Pace-related gait differences between groups, temporal gait variables were not different between mTBI and controls groups in the home setting.[31] Since turning occurs frequently at home is more complex than straight gait, turning may be an important element of gait assessment for the chronic mTBI population.

We observed slightly more deficits in the mTBI group when walking while performing a secondary task, but no group differences in dual-task cost was observed. These results suggest that adding a dual-task assessment uncovers an underlying gait deficits that may be compensated for when just assessing gait by itself. These findings agree with the acute mTBI literature that reports dual-task gait deficits up to a month after injury.[54, 55] In fact, dual-task assessments, including dual-task cost, have been suggested as an important element to add to evaluations after mTBI.[56, 57] Further, dual-task assessments could prove to be an important outcome in clinical evaluations in chronic, symptomatic mTBI populations, as highlighted in older adults.[58] However, the dual-task cost on gait was not different between groups herein, which suggests both groups' gait performance decreased at a similar rate as a result of the secondary task. Our results suggest it is important to measure performance with a dual-task, yet do not provide evidence that calculating dual-task cost as a separate measure will add benefit to the analysis.

Gait was associated with symptom severity, particularly in NSI somatic sub-score. The NSI somatic sub-score includes items that are conceivably associated with gait performance, such as dizziness, feeling uncoordinated, and balance dysfunction.[48] Specifically, the dual-task domains Variability and Turning related to somatic symptom severity while only Variability single-task domain related to somatic symptom severity. The magnitudes of the relationships between symptom severity and gait Variability were similar across single- and dual-task gait conditions in this cohort. While we did not observe group

differences for gait Variability, the effect sizes for single- (0.38) and dual-task (0.36) suggest that gait Variability warrants further investigation in the chronic mTBI population.

Cumulatively, these results suggest people with mTBI may have decreased gait automaticity (the ability to complete gait without directing attention to the task).[59] Assessing gait under single- and dual-task conditions permits the ability to assess gait automaticity.[60-62] Deterioration in gait automaticity could be a secondary indicator of global cognitive deficits that, when identified, could be addressed by a clinician during the recovery process.[63] Deterioration of gait automaticity is observed in other neuropathological populations, especially as the complexity of the gait task increases,[60-62] and has a negative impact on quality of life in older and cognitively impaired populations.[37, 64-66] While the symptomatic chronic mTBI population reports a decreased quality of life due to emotional and cognitive impairments,[4-7] our results suggest gait dysfunction may be another factor in poorer quality of life in this population. Dual-tasking diverts attentional resources from the gait task to the cognitive task, resulting in an increased cognitive load to complete both tasks successfully.[29] The neurophysiological dysfunction responsible for the symptoms reported on the NSI such as visual disturbances could be a factor in the observed gait dysfunction in the mTBI group.

To date, the majority of investigations that assess gait in chronic mTBI do so in asymptomatic populations or do not report the symptom severity.[11] Further, most studies report only Pace-related gait characteristics with inconsistent results reported.[10, 11, 17] The inconsistencies in results could suggest that people with a mTBI history, who report no persisting symptoms, exhibit no motor control deficits as a result of possible persistent neurophysiological dysfunction. However, the consistent turning and dual-task gait dysfunction, combined with relationships with both cognitive and somatic mTBI symptoms, may suggest persistent sub-clinical neurophysiological dysfunction.

Limitations. There are inherent limitations to the interpretation of these results. First, the use of wearable inertial sensors are not yet commonplace in clinics, so the findings may not be generalizable to clinical setting at this stage. Additionally, the mechanism of injury in this mTBI group was not limited to a single mechanism (e.g. athletic exposure, motor vehicle accident, blast injury). Though there is still limited knowledge on the link between specific mechanisms of injury and different signs and symptoms, it is possible that heterogeneity within the mTBI exposures dilutes the findings that may otherwise be seen in a more homogeneous group analysis. Lastly, medical history was not verified in the control participants, we relied on self-reported mTBI history.

To conclude, people with chronic mTBI and persistent symptoms exhibited altered gait, particularly under dual-task, compared to healthy controls. Additionally, worse gait performance related to greater symptom severity. Specifically, increased symptom severity was associated with more Variability and slower Pace and Turning, particularly under the dual-task gait condition. Thus, increasing the complexity of the gait assessment appears to help differentiate people with gait deficits in this population and this approach may help improve assessments. Clinical research investigating gait in this population may benefit from analyzing multiple gait domains as a way to reduce type II error and the variability of reported gait characteristic differences. Future investigations should assess complex gait tasks and account for symptom severity in chronic mTBI populations to avoid missing gait deficits in this population.

Acknowledgements

This study was supported by the Assistant Secretary of Defense for Health Affairs under the Award Number W81XWH-15-0620. All interpretations and opinions are those of the author and are not necessarily endorsed by the Department of Defense.

Author Disclosure Statement

The authors have no conflicts of interest.

References

1. Kamins, J., Bigler, E., Covassin, T., Henry, L., Kemp, S., Leddy, J.J., Mayer, A., McCrea, M., Prins, M., Schneider, K.J., Valovich McLeod, T.C., Zemek, R. and Giza, C.C. (2017). What is the physiological time to recovery after concussion? A systematic review. Br J Sports Med 51, 935-940.
2. McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., Cantu, R.C., Cassidy, D., Echemendia, R.J., Castellani, R.J., Davis, G.A., Ellenbogen, R., Emery, C., Engebretsen, L., Feddermann-Demont, N., Giza, C.C., Guskiewicz, K.M., Herring, S., Iverson, G.L., Johnston, K.M., Kissick, J., Kutcher, J., Leddy, J.J., Maddocks, D., Makdissi, M., Manley, G.T., McCrea, M., Meehan, W.P., Nagahiro, S., Patricios, J., Putukian, M., Schneider, K.J., Sills, A., Tator, C.H., Turner, M. and Vos, P.E. (2017). Consensus statement on concussion in sport-the 5(th) international conference on concussion in sport held in Berlin, October 2016. Br J Sports Med 51, 838-847.
3. Nelson, L.D., Temkin, N.R., Dikmen, S., Barber, J., Giacino, J.T., Yuh, E., Levin, H.S., McCrea, M.A., Stein, M.B., Mukherjee, P., Okonkwo, D.O., Diaz-Arrastia, R., Manley, G.T., and the, T.-T.B.I.I., Adeoye, O., Badjatia, N., Boase, K., Bodien, Y., Bullock, M.R., Chesnut, R., Corrigan, J.D., Crawford, K., Mis, Duhaime, A.C., Ellenbogen, R., Feeser, V.R., Ferguson, A., Foreman, B., Gardner, R., Gaudette, E., Gonzalez, L., Gopinath, S., Gullapalli, R., Hemphill, J.C., Hotz, G., Jain, S., Korley, F., Kramer, J., Kreitzer, N., Lindsell, C., Machamer, J., Madden, C., Martin, A., McAllister, T., Merchant, R., Noel, F., Palacios, E., Perl, D., Puccio, A., Rabinowitz, M., Robertson, C.S., Rosand, J., Sander, A., Satris, G., Schnyer, D., Seabury, S., Sherer, M., Taylor, S., Toga, A., Valadka, A., Vassar, M.J., Vespa, P., Wang, K., Yue, J.K. and Zafonte, R. (2019). Recovery After Mild Traumatic Brain Injury in Patients Presenting to US Level I Trauma Centers: A Transforming Research and Clinical Knowledge in Traumatic Brain Injury (TRACK-TBI) Study. JAMA Neurol.
4. Mac Donald, C.L., Barber, J., Patterson, J., Johnson, A.M., Dikmen, S., Fann, J.R. and Temkin, N. (2019). Association between 5-year clinical outcome in patients with nonmedically evacuated mild blast traumatic brain injury and clinical measures collected within 7 days postinjury in combat. JAMA network open 2, e186676-e186676.
5. Theadom, A., Starkey, N., Barker-Collo, S., Jones, K., Ameratunga, S., Feigin, V. and Group, B.I.y.R. (2018). Population-based cohort study of the impacts of mild traumatic brain injury in adults four years post-injury. PLoS One 13, e0191655.
6. Schiehser, D.M., Twamley, E.W., Liu, L., Matevosyan, A., Filoteo, J.V., Jak, A.J., Orff, H.J., Hanson, K.L., Sorg, S.F. and Delano-Wood, L. (2015). The Relationship Between Postconcussive Symptoms and Quality of Life in Veterans With Mild to Moderate Traumatic Brain Injury. J Head Trauma Rehabil 30, E21-28.
7. King, N.S. and Kirwilliam, S. (2011). Permanent post-concussion symptoms after mild head injury. Brain Inj 25, 462-470.
8. Parker, T.M., Osternig, L.R., Van Donkelaar, P. and Chou, L.S. (2006). Gait stability following concussion. Medicine and Science in Sports and Exercise 38, 1032-1040.
9. Buckley, T.A., Munkasy, B.A., Tapia-Lovler, T.G. and Wikstrom, E.A. (2013). Altered gait termination strategies following a concussion. Gait Posture 38, 549-551.
10. Fino, P.C., Nussbaum, M.A. and Brolinson, P.G. (2016). Locomotor deficits in recently concussed athletes and matched controls during single and dual-task turning gait: preliminary results. Journal of neuroengineering and rehabilitation 13, 65.
11. Fino, P.C., Parrington, L., Pitt, W., Martini, D.N., Chesnutt, J.C., Chou, L.S. and King, L.A. (2018). Detecting gait abnormalities after concussion or mild traumatic brain injury: A systematic review of single-task, dual-task, and complex gait. Gait Posture 62, 157-166.
12. Findling, O., Schuster, C., Sellner, J., Ettlin, T. and Allum, J.H. (2011). Trunk sway in patients with and without, mild traumatic brain injury after whiplash injury. Gait Posture 34, 473-478.

13. Pape, M.M., Williams, K., Kodosky, P.N. and Dretsch, M. (2016). The Community Balance and Mobility Scale: A Pilot Study Detecting Impairments in Military Service Members With Comorbid Mild TBI and Psychological Health Conditions. J Head Trauma Rehabil 31, 339-345.
14. Cossette, I., Ouellet, M.C. and McFadyen, B.J. (2014). A preliminary study to identify locomotor-cognitive dual tasks that reveal persistent executive dysfunction after mild traumatic brain injury. Arch Phys Med Rehabil 95, 1594-1597.
15. Fino, P.C. (2016). A preliminary study of longitudinal differences in local dynamic stability between recently concussed and healthy athletes during single and dual-task gait. Journal of Biomechanics.
16. Martini, D.N., Sabin, M.J., DePesa, S.A., Leal, E.W., Negrete, T.N., Sosnoff, J.J. and Broglio, S.P. (2011). The chronic effects of concussion on gait. Arch Phys Med Rehabil 92, 585-589.
17. Buckley, T.A., Vallabhajosula, S., Oldham, J.R., Munkasy, B.A., Evans, K.M., Krazeise, D.A., Ketcham, C.J. and Hall, E.E. (2016). Evidence of a conservative gait strategy in athletes with a history of concussions. Journal of sport and health science 5, 417-423.
18. Martini, D.N., Goulet, G.C., Gates, D.H. and Broglio, S.P. (2016). Long-term effects of adolescent concussion history on gait, across age. Gait Posture 49, 264-270.
19. Catena, R.D., van Donkelaar, P., Halterman, C.I. and Chou, L.S. (2009). Spatial orientation of attention and obstacle avoidance following concussion. Exp Brain Res 194, 67-77.
20. Robitaille, N., Jackson, P.L., Hébert, L.J., Mercier, C., Bouyer, L.J., Fecteau, S., Richards, C.L. and McFadyen, B.J. (2017). A Virtual Reality avatar interaction (VRai) platform to assess residual executive dysfunction in active military personnel with previous mild traumatic brain injury: proof of concept. Disability and Rehabilitation: Assistive Technology 12, 758-764.
21. Lord, S., Galna, B. and Rochester, L. (2013). Moving forward on gait measurement: toward a more refined approach. Mov Disord 28, 1534-1543.
22. Lord, S., Galna, B., Verghese, J., Coleman, S., Burn, D. and Rochester, L. (2013). Independent domains of gait in older adults and associated motor and nonmotor attributes: validation of a factor analysis approach. J Gerontol A Biol Sci Med Sci 68, 820-827.
23. Verghese, J., Wang, C., Lipton, R.B., Holtzer, R. and Xue, X. (2007). Quantitative gait dysfunction and risk of cognitive decline and dementia. J Neurol Neurosurg Psychiatry 78, 929-935.
24. Morris, R., Martini, D.N., Smulders, K., Kelly, V.E., Zabetian, C.P., Poston, K., Hiller, A., Chung, K.A., Yang, L. and Hu, S.-C. (2019). Cognitive associations with comprehensive gait and static balance measures in Parkinson's disease. Parkinsonism & Related Disorders.
25. Stuart, S., Parrington, L., Morris, R., Martini, D.N., Fino, P.C. and King, L.A. (2020). Gait measurement in chronic mild traumatic brain injury: A model approach. Human Movement Science 69, 102557.
26. Pape, M.M., Kodosky, P.N. and Hoover, P. (2019). The Community Balance and Mobility Scale: Detecting Impairments in Military Service Members With Mild Traumatic Brain Injury. Mil Med.
27. Scherer, M.R., Weightman, M.M., Radomski, M.V., Davidson, L.F. and McCulloch, K.L. (2013). Returning service members to duty following mild traumatic brain injury: exploring the use of dual-task and multitask assessment methods. Phys Ther 93, 1254-1267.
28. Bayot, M., Dujardin, K., Tard, C., Defebvre, L., Bonnet, C.T., Allart, E. and Delval, A. (2018). The interaction between cognition and motor control: A theoretical framework for dual-task interference effects on posture, gait initiation, gait and turning. Neurophysiol Clin 48, 361-375.
29. Woollacott, M. and Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 16, 1-14.
30. Fino, P.C., Parrington, L., Walls, M., Sippel, E., Hullar, T.E., Chesnutt, J.C. and King, L.A. (2018). Abnormal Turning and Its Association with Self-Reported Symptoms in Chronic Mild Traumatic Brain Injury. J Neurotrauma 35, 1167-1177.

31. Stuart, S., Parrington, L., Martini, D.N., Kreter, N., Chesnutt, J.C., Fino, P.C. and King, L.A. (2019). Analysis of Free-Living Mobility in People with Mild Traumatic Brain Injury and Healthy Controls: Quality over Quantity. J Neurotrauma.
32. Demakakos, P., Cooper, R., Hamer, M., de Oliveira, C., Hardy, R. and Breeze, E. (2013). The bidirectional association between depressive symptoms and gait speed: evidence from the English Longitudinal Study of Ageing (ELSA). PLoS One 8, e68632.
33. Patience, J., Lai, K.S.P., Russell, E., Vasudev, A., Montero-Odasso, M. and Burhan, A.M. (2019). Relationship between mood, thinking and walking: a systematic review examining depressive symptoms, executive function, and gait. The American Journal of Geriatric Psychiatry.
34. Helbostad, J.L., Leirfall, S., Moe-Nilssen, R. and Sletvold, O. (2007). Physical fatigue affects gait characteristics in older persons. J Gerontol A Biol Sci Med Sci 62, 1010-1015.
35. Michalak, J., Troje, N.F., Fischer, J., Vollmar, P., Heidenreich, T. and Schulte, D. (2009). Embodiment of sadness and depression--gait patterns associated with dysphoric mood. Psychosom Med 71, 580-587.
36. Morrison, S., Colberg, S.R., Parson, H.K., Neumann, S., Handel, R., Vinik, E.J., Paulson, J. and Vinik, A.I. (2016). Walking-Induced Fatigue Leads to Increased Falls Risk in Older Adults. J Am Med Dir Assoc 17, 402-409.
37. Montero-Odasso, M., Muir, S.W. and Speechley, M. (2012). Dual-task complexity affects gait in people with mild cognitive impairment: the interplay between gait variability, dual tasking, and risk of falls. Arch Phys Med Rehabil 93, 293-299.
38. Verghese, J., Robbins, M., Holtzer, R., Zimmerman, M., Wang, C., Xue, X. and Lipton, R.B. (2008). Gait dysfunction in mild cognitive impairment syndromes. J Am Geriatr Soc 56, 1244-1251.
39. Frenkel-Toledo, S., Giladi, N., Peretz, C., Herman, T., Gruendlinger, L. and Hausdorff, J.M. (2005). Effect of gait speed on gait rhythmicity in Parkinson's disease: variability of stride time and swing time respond differently. J Neuroeng Rehabil 2, 23.
40. Bryant, M.S., Rintala, D.H., Hou, J.G., Charness, A.L., Fernandez, A.L., Collins, R.L., Baker, J., Lai, E.C. and Protas, E.J. (2011). Gait variability in Parkinson's disease: influence of walking speed and dopaminergic treatment. Neurol Res 33, 959-964.
41. Fino, P.C., Peterka, R.J., Hullar, T.E., Murchison, C., Horak, F.B., Chesnutt, J.C. and King, L.A. (2017). Assessment and rehabilitation of central sensory impairments for balance in mTBI using auditory biofeedback: a randomized clinical trial. BMC neurology 17, 41.
42. VA/DoD Clinical Practice Guideline (2009). VA/DoD clinical practice guideline for management of concussion/mild traumatic brain injury. J Rehabil Res Dev 46.
43. Moore, S.A., Hickey, A., Lord, S., Del Din, S., Godfrey, A. and Rochester, L. (2017). Comprehensive measurement of stroke gait characteristics with a single accelerometer in the laboratory and community: a feasibility, validity and reliability study. Journal of neuroengineering and rehabilitation 14, 130.
44. Morris, R., Stuart, S., McBarron, G., Fino, P.C., Mancini, M. and Curtze, C. (2019). Validity of Mobility Lab (version 2) for gait assessment in young adults, older adults and Parkinson’s disease. Physiological measurement 40, 095003.
45. Shor, R.E. (1975). An auditory analog of the Stroop Test. J Gen Psychol 93, 281-288.
46. Cicerone, K.D. and Kalmar, K. (1995). Persistent postconcussion syndrome: the structure of subjective complaints after mild traumatic brain injury. The journal of head trauma rehabilitation.
47. Meterko, M., Baker, E., Stolzmann, K.L., Hendricks, A.M., Cicerone, K.D. and Lew, H.L. (2012). Psychometric assessment of the Neurobehavioral Symptom Inventory-22: the structure of persistent postconcussive symptoms following deployment-related mild traumatic brain injury among veterans. J Head Trauma Rehabil 27, 55-62.

48. King, P.R., Donnelly, K.T., Donnelly, J.P., Dunnam, M., Warner, G., Kittleson, C.J., Bradshaw, C.B., Alt, M. and Meier, S.T. (2012). Psychometric study of the Neurobehavioral Symptom Inventory. J Rehabil Res Dev 49, 879-888.
49. Caplan, L.J., Ivins, B., Poole, J.H., Vanderploeg, R.D., Jaffee, M.S. and Schwab, K. (2010). The structure of postconcussive symptoms in 3 US military samples. The Journal of Head Trauma Rehabilitation 25, 447-458.
50. Cohen, J. (1977). Statistical power analysis for the behavioral sciences (rev. Lawrence Erlbaum Associates, Inc.
51. Mancini, M., El-Gohary, M., Pearson, S., McNames, J., Schlueter, H., Nutt, J.G., King, L.A. and Horak, F.B. (2015). Continuous monitoring of turning in Parkinson's disease: Rehabilitation potential. NeuroRehabilitation 37, 3-10.
52. Takei, Y., Grasso, R., Amorim, M.-A. and Berthoz, A. (1997). Circular trajectory formation during blind locomotion: a test for path integration and motor memory. Experimental Brain Research 115, 361-368.
53. Takei, Y., Grasso, R. and Berthoz, A. (1996). Quantitative analysis of human walking trajectory on a circular path in darkness. Brain research bulletin 40, 491-495.
54. Howell, D.R., Beasley, M., Vopat, L. and Meehan, W.P., 3rd (2017). The Effect of Prior Concussion History on Dual-Task Gait following a Concussion. J Neurotrauma 34, 838-844.
55. Howell, D.R., Osternig, L.R. and Chou, L.S. (2015). Return to activity after concussion affects dual-task gait balance control recovery. Med Sci Sports Exerc 47, 673-680.
56. McCulloch, K. (2007). Attention and dual-task conditions: physical therapy implications for individuals with acquired brain injury. Journal of Neurologic Physical Therapy 31, 104-118.
57. Weightman, M.M., Bolgla, R., McCulloch, K.L. and Peterson, M.D. (2010). Physical therapy recommendations for service members with mild traumatic brain injury. The Journal of head trauma rehabilitation 25, 206-218.
58. Manor, B., Zhou, J., Lo, O.Y., Zhu, H., Gouskova, N.A., Yu, W., Zafonte, R., Lipsitz, L.A., Travison, T.G. and Pascual-Leone, A. (2020). Self-Reported Head Trauma Predicts Poor Dual Task Gait in Retired National Football League Players. Annals of neurology 87, 75-83.
59. Bernstein, N. (1966). The co-ordination and regulation of movements. The co-ordination and regulation of movements.
60. Gilat, M., Bell, P.T., Ehgoetz Martens, K.A., Georgiades, M.J., Hall, J.M., Walton, C.C., Lewis, S.J.G. and Shine, J.M. (2017). Dopamine depletion impairs gait automaticity by altering cortico-striatal and cerebellar processing in Parkinson's disease. NeuroImage 152, 207-220.
61. Vandenbossche, J., Deroost, N., Soetens, E., Coomans, D., Spildooren, J., Vercruysse, S., Nieuwboer, A. and Kerckhofs, E. (2012). Freezing of gait in Parkinson's disease: disturbances in automaticity and control. Front Hum Neurosci 6, 356.
62. Clark, D.J. (2015). Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies. Front Hum Neurosci 9, 246.
63. Allali, G., Van Der Meulen, M. and Assal, F. (2010). Gait and cognition: The impact of executive function. Swiss Archives of Neurology and Psychiatry 161, 195-199.
64. Callisaya, M.L., Blizzard, L., Schmidt, M.D., Martin, K.L., McGinley, J.L., Sanders, L.M. and Srikanth, V.K. (2011). Gait, gait variability and the risk of multiple incident falls in older people: a population-based study. Age Ageing 40, 481-487.
65. Hausdorff, J.M., Balash, J. and Giladi, N. (2003). Effects of cognitive challenge on gait variability in patients with Parkinson's disease. J Geriatr Psychiatry Neurol 16, 53-58.
66. Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E.S. and Hausdorff, J.M. (2006). Dual-tasking effects on gait variability: the role of aging, falls, and executive function. Mov Disord 21, 950-957.

Table 1: Demographic Information

	Control	mTBI	*p* value
n	57	65	NA
Gender (F)	36	45	0.335
Age (yrs)	36.9 (12.2)	39.6 (11.7)	0.218
Height (m)	1.7 (0.1)	1.7 (0.2)	0.235
Mass (Kg)	75.2 (19.0)	83.0 (30.5)	0.095
Time from mTBI (yrs)	NA	1.0 (13.0)	NA
Total Previous mTBIs	NA	1.5 (9.0)	NA
NSI Total*	**3.3 (3.2)**	**37.1 (14.9)**	**<0.001**
NSI Somatic*	**0.9 (1.1)**	**15.4 (7.3)**	**<0.001**
NSI Affective*	**1.7 (2.0)**	**13.3 (5.9)**	**<0.001**
NSI Cognitive*	**0.7 (1.1)**	**8.4 (4.0)**	**<0.001**

Mean (SD). Time from most recent mTBI and total previous mTBIs are presented as median (range).

Table 2: Gait Domain Scores

		Control	mTBI	F Statistic	*P* value	Cohen's *d*
ST	Stroop Acc (%)	98.8 (4.2)	97.7 (6.3)	$F_{(1,96)} = 1.25$	0.267	0.23
	Pace	**0.38 (0.73)**	**-0.32 (0.82)**	**$F_{(1,109)} = 22.56$**	**<0.001**	**0.91**
	Variability	-0.15 (0.76)	0.14 (0.82)	$F_{(1,109)} = 3.88$	0.051	0.38
	Rhythm	0.06 (0.32)	-0.09 (0.35)	$F_{(1,109)} = 5.39$	0.022	0.45
	Turning	**0.38 (0.85)**	**-0.31 (0.85)**	**$F_{(1,109)} = 18.15$**	**<0.001**	**0.82**
DT	Stroop Acc (%)	98.5 (1.7)	95.8 (7.8)	$F_{(1,96)} = 5.53$	0.021	0.48
	Pace	**0.39 (0.80)**	**-0.32 (0.85)**	**$F_{(1,108)} = 29.99$**	**<0.001**	**0.87**
	Variability	-0.13 (0.72)	0.18 (1.00)	$F_{(1,108)} = 3.44$	0.066	0.36
	Rhythm	**0.10 (0.28)**	**-0.11 (0.37)**	**$F_{(1,108)} = 10.86$**	**0.001**	**0.64**
	Turning	**0.37 (0.61)**	**-0.33 (1.05)**	**$F_{(1,112)} = 17.73$**	**<0.001**	**0.81**
DTC	Stroop Acc	-0.13 (5.80)	-1.72 (6.32)	$F_{(1,96)} = 1.68$	0.198	0.27
	Pace	0.06 (0.33)	-0.03 (0.56)	$F_{(1,111)} = 1.09$	0.298	0.20
	Variability	-0.02 (0.52)	0.05 (0.61)	$F_{(1,108)} = 0.44$	0.510	0.13
	Rhythm	-0.03 (0.04)	0.05 (0.43)	$F_{(1,108)} = 1.08$	0.302	0.20
	Turning	-0.25 (0.79)	0.18 (0.83)	$F_{(1,108)} = 7.79$	0.006	0.54

Mean (SD).

Table 3: Individual Gait Characteristics

			Control	mTBI
ST	Pace	Stride Length (m)	1.31 (0.11)	1.22 (0.12)
		Gait Speed (m/s)	1.21 (0.14)	1.10 (0.14)
		Foot Strike Angle (°)	26.12 (3.69)	23.70 (3.69)
	Variability	Double Support (% of Gait Cycle)	0.96 (0.23)	1.05 (0.28)
		Stride Length Variability (m)	0.04 (0.01)	0.04 (0.01)
		Foot Strike Angle Variability (°)	1.57 (0.42)	1.65 (0.37)
		Single Support (% of Gait Cycle)	0.63 (0.14)	0.69 (0.16)
		Stride Time Variability (s)	0.02 (0.01)	0.02 (0.01)
	Rhythm	Double Support Variability (% of Gait Cycle)	19.13 (2.84)	20.81 (2.86)
		Stride Time (s)	1.09 (0.07)	1.12 (0.08)
		Single Support Variability (% of Gait Cycle)	40.43 (1.43)	39.59 (1.43)
	Turning	Turn Duration (s)	2.07 (0.34)	2.32 (0.41)
		Peak Turn Velocity (°/s)	196.85 (40.51)	163.89 (32.19)
DT	Pace	Stride Length (m)	1.29 (0.12)	1.19 (0.13)
		Gait Speed (m/s)	1.20 (0.15)	1.06 (0.16)
		Foot Strike Angle (°)	25.18 (4.18)	22.93 (3.86)
	Variability	Double Support Variability (% of Gait Cycle)	0.94 (0.23)	1.04 (0.35)
		Stride Length Variability (m)	0.03 (0.01)	0.03 (0.01)
		Foot Strike Angle Variability (°)	1.47 (0.35)	1.53 (0.40)
		Single Support Variability (% of Gait Cycle)	0.61 (0.13)	0.67 (0.21)
		Stride Time Variability (s)	0.02 (0.01)	0.03 (0.01)
	Rhythm	Double Support (% of Gait Cycle)	19.24 (2.58)	21.61 (3.22)
		Stride Time (s)	1.09 (0.07)	1.14 (0.10)
		Single Support (% of Gait Cycle)	40.38 (1.29)	39.20 (1.60)
	Turning	Turn Duration (s)	2.05 (0.38)	2.68 (1.55)
		Peak Turn Velocity (°/s)	203.74 (46.53)	159.97 (44.99)
DTC	Pace	Stride Length (%)	-1.27 (2.82)	-1.43 (3.97)
		Gait Speed (%)	-1.20 (4.54)	-1.77 (7.34)
		Foot Strike Angle (%)	-3.68 (5.37)	-2.96 (5.04)
	Variability	Double Support Variability (%)	-1.24 (17.67)	-0.79 (17.51)
		Stride Length Variability (%)	-5.82 (26.93)	-5.03 (22.14)
		Foot Strike Angle Variability (%)	-5.37 (18.20)	-6.23 (16.65)
		Single Support Variability (%)	-4.12 (12.64)	-2.71 (13.78)
		Stride Time Variability (%)	4.94 (35.37)	10.50 (41.31)
	Rhythm	Double Support (%)	1.53 (4.35)	2.22 (7.28)
		Stride Time (%)	0.02 (2.52)	2.13 (6.68)
		Single Support (%)	-0.30 (0.95)	-0.98 (2.19)
	Turning	Turn Duration (%)	-0.51 (8.46)	4.26 (8.49)
		Peak Turn Velocity (%)	2.66 (8.49)	-0.25 (10.41)

Mean(SD). Each gait characteristic is grouped with the other gait characteristics of the same gait domain.

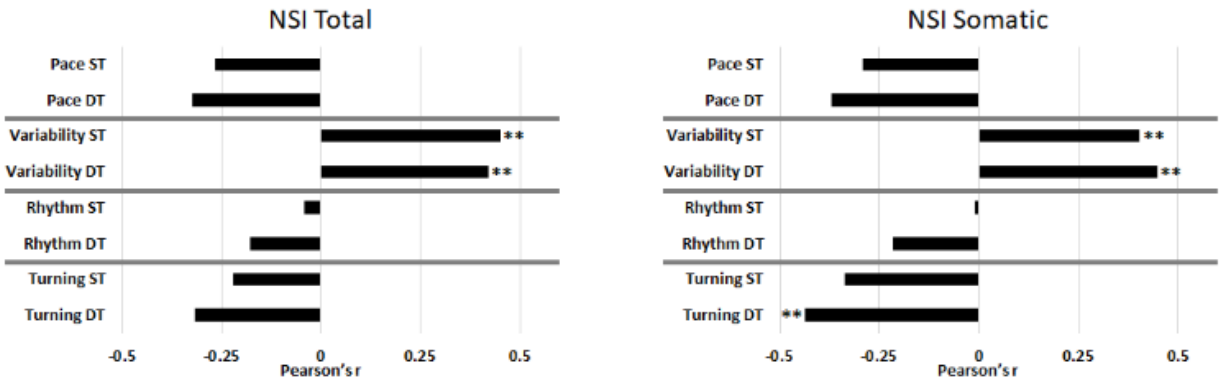

Figure 1: Pearson's correlations r-values for NSI Total score (Left) and NSI Somatic sub-score (Right) with the ST and DT gait domains (within chronic mTBI group only). ST = single-task; DT = dual-task. * indicates $p < 0.01$; ** indicates $p < 0.003$.