A Longitudinal Spatiotemporal Analysis of Gait after Traumatic Brain Injury and an Assessment of Rhythmic Auditory Stimulation as a Gait Training Technique

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science
Rehabilitation Sciences Institute
University of Toronto

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Abstract
Traumatic brain injury (TBI) can result in an array of motor and cognitive impairments. Walking difficulties are common following injury and can limit an individual’s ability to regain independence and achieve community integration. Rehabilitation is commonly used to treat gait-related issues and is in constant need of advancement and refinement. This thesis investigates: (1) the longitudinal change in spatiotemporal features of gait in the first year following TBI and the relationship between these changes and community integration, and (2) the feasibility of rhythmic auditory stimulation (RAS) as a gait training intervention to address chronic gait impairments of individuals living in the community with a TBI. Patterns of longitudinal spatiotemporal change are described and distinctions between severity groups are clarified. Next, the concurrent and predictive relationship between gait and community integration is elucidated. Lastly, the feasibility of RAS as a gait training technique in chronic TBI is further explored.
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<td>ABI</td>
<td>Acquired brain injury</td>
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<tr>
<td>ABC Scale</td>
<td>The Activities-specific Balance Confidence (ABC) Scale</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
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<tr>
<td>RPE</td>
<td>Borg Rating of Perceived Exertion Scale</td>
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<tr>
<td>CV</td>
<td>Coefficient of variation</td>
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<td>COGT</td>
<td>Conventional over ground training</td>
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<tr>
<td>CB&amp;M</td>
<td>Community Balance and Mobility Scale</td>
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<tr>
<td>CIQ</td>
<td>Community Integration Questionnaire</td>
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<tr>
<td>EMG</td>
<td>Electromyographic</td>
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<tr>
<td>FES</td>
<td>Functional Electrical Stimulation</td>
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<tr>
<td>GCS</td>
<td>Glasgow Coma Scale</td>
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<tr>
<td>HiMAT</td>
<td>High Level Mobility Assessment Tool</td>
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<tr>
<td>LPTA</td>
<td>Length of post-traumatic amnesia</td>
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<tr>
<td>LOC</td>
<td>Loss of Consciousness</td>
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<tr>
<td>MP</td>
<td>Maximum pace</td>
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<tr>
<td>MoCA</td>
<td>Montreal Cognitive Assessment Tool</td>
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<tr>
<td>MVA</td>
<td>Motor Vehicle Accident</td>
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<tr>
<td>NMT</td>
<td>Neurological Music Therapist</td>
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<td>NT</td>
<td>Neurotypical</td>
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<td>Parkinson’s Disease</td>
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<td>Participant 1</td>
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<td>PP</td>
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<td>TSI</td>
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<td>TBI</td>
<td>Traumatic Brain Injury</td>
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<td>BWSTT</td>
<td>Body-weight supported treadmill training</td>
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<td>6MWT</td>
<td>Six Minute Walk Test</td>
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1 Introduction

1.1 Traumatic brain injury

1.1.1 Background to traumatic brain injury
A traumatic brain injury (TBI) occurs when an external force induces a change in brain function (1). These injuries can arise from a variety of causes, including motor vehicle accidents (MVA), falls, violence, and sports-related injuries (2). Following brain trauma, individuals may experience any combination of cognitive, motor, and behavioral impairments (3–5). By comparison to other injuries (e.g., orthopedic and spinal cord injuries), TBI is the leading cause of mortality and morbidity and has been recognized as a critical health issue in North America (6). According to the Canadian Institute for Health Information, between 2003-2004, there were 16,811 hospital admissions for TBI, amounting to 46 admissions per day (2). The majority of patients that survive a TBI will spend a significant portion of time post-injury participating in rehabilitation. These motor and cognitive interventions are imperative to not only reduce injury-related morbidity and dependency but also to decrease costs associated with TBI (7–12).

1.1.2 Classifying injury severity
Severe TBI can result in significant impairments to cognitive, motor, and psychological functioning and will be the primary focus of this thesis (13). Injury severity can be classified by the Glasgow Coma Scale (GCS) score, length of loss of consciousness (LOC), or length of posttraumatic amnesia (LPTA). In the present thesis, LPTA will be the classification system used to demark varying degrees of injury severity. Post-traumatic amnesia (PTA) is the inability to recall events immediately before and after injury and is significantly associated with post-injury outcomes (14–17). There are 3 LPTA groups associated with severe TBI: 1-7 days = severe, 1-4 weeks = very severe, and >4 weeks = extremely severe (18). Throughout this thesis, injury severity will be assessed and reported according to this classification.

1.1.3 Motor impairments and recovery
A major focus of rehabilitation interventions following TBI is addressing neuromotor impairments (19–23). Previous research has attempted to examine the longitudinal pattern of neuromotor recovery after TBI (3,8,16,17,24–33). Many reviews and recent neuroimaging studies provide detailed descriptions of motor deficits, recovery, and rehabilitation following
TBI in animals and humans as well as discussions regarding the underlying neural impairments (32,34–38). Motor recovery, as measured by a therapist's assessments of muscle tone, range of motion, abnormal and voluntary movement, and motor skills such as sitting, kneeling, standing and walking, typically transpired in a sequential pattern during the first few weeks post-injury (24,26). Prior investigations have used clinical measures such as the Functional Independence Measure scores to assess the degree of physical independence post-injury (25,26), and some have reported early recovery in this measure (8,39–41). However, other studies have raised caution surrounding these findings, noting that individuals with seemingly good motor recovery may still present with residual deficits in the planning and execution of motor movements due to damage and compensations associated with the underlying brain areas responsible for these functions (e.g., cerebellum or pre-motor area) (37,38,42–48). Motor impairments can negatively influence an individual’s quality-of-life, cause early mortality, heighten caregiver burden, and incur substantial financial costs (9,49–54).

1.2 Gait impairments
A majority of individuals obtain the ability to walk independently (24,33,55) (or independently with an assistive device) (27) by 6 weeks post-injury. Though this finding demonstrates the wonders of both neuroplasticity and rehabilitation services, evidence suggests that gait-related issues remain present, particularly in relation to measures of forward progression (i.e., speed, cadence and step length) (28–30,42,47,56–59), kinematics/kinetics/muscle activation of the lower limb (57–61), stability (29,48,58,62–74), symmetry (28,31,48,56,75–80), and ability to dual-task (64,81–83). Unaddressed gait abnormalities place individuals recovering from TBI at a higher risk of falls and limited community integration (65,84–87). Gait impairments after TBI have been examined using a variety of methods, such as kinematic, kinetic, muscular, neuroimaging, and spatiotemporal approaches; however, due to the diffuse nature of brain injury, it is more challenging to define gait characteristics post-TBI compared to other neurological disorders (e.g. stroke and Parkinson’s Disease (PD)) (48,59,61,75).
1.2.1 Characterizing gait using kinematic, kinetic, centre-of-mass, and muscle activation patterns

Three-dimensional gait analysis has been used in a variety of different walking conditions to assess the kinematic and kinetic deviations in gait following TBI (58–60,62,70,88–91). In 2009, Williams and coauthors (58) assessed 41 individuals with an LPTA >4 weeks and determined that 6 of 12 kinematic and kinetic gait variables were different from neurotypical (NT) controls. As a whole, the most commonly reported abnormalities was excessive knee joint angle at initial contact and uncoordinated trunk and pelvic movement (58). Williams and coauthors (58) highlight the importance in characterizing these differences in pelvic, knee, and ankle joint abnormalities to pair an individual with the appropriate gait interventions. Tailoring specifically designed interventions to meet individualized gait needs has been the goal of Williams et al. for many years.

Kinematic and kinetic variables provide additional information to explain spatiotemporal outcomes of the gait cycle. For instance, Williams et al. (58) found that a reduced push-off terminal stance strength was abnormal in 64% of participants who walked with a slow gait speed, while a stiff-legged gait pattern (knee extension in the swing phase) was present in 52% of slow walkers. Research efforts have concluded that slow asymmetrical gait patterns often arise post-TBI as a result of reduced ankle power generation (78,85). However, common deviations in kinematic measures such as pelvic rotation have yet to be linked to specific spatiotemporal variables other than speed (i.e., step variability and symmetry ratios) in TBI literature. Recently, Acuna et al (61) built upon the work of Williams et al. (49) and characterized the pattern of muscle activation using electromyography (EMG) analysis in a group of individuals (n=44) on average 6.3 years (SD=7.6) post-injury. This cross-sectional study concluded that individuals, at least 1-year post-TBI, had abnormal temporal muscle coordination during overground walking in the tibialis anterior, medial gastrocnemius, and rectus femoris muscle compared to NT controls (61).

Abnormalities in kinematic and kinetic measures of gait have also been linked to challenging walking tasks, such as maximum paced (MP) walking (57). Individuals with TBI demonstrate a different pattern of lower limb power generation than NT controls when increasing walking
speeds from preferred pace (PP) to MP speeds (57). When asked to increase walking speeds, NT controls demonstrated a proportional increase in all 3 joint power variables: (1) peak ankle power generation at push-off, (2) peak hip power generation during initial stance, and (3) peak hip power generation during pre-swing (57). After TBI, however, individuals relied on hip power generation as compensation for reduced ankle power generation (57). During MP walking, individuals with a TBI were able to match speeds with NT controls, but could not reduce lateral centre-of-mass displacement (57). Williams et al. (57) noted that a larger lateral centre-of-mass displacement following TBI was associated with a broader base of support. The authors concluded that individuals post-TBI could walk fast but demonstrated underlying spatiotemporal adaptations, suggesting instability at these speeds (57).

Kinematic, kinetic, and centre-of-mass features of gait can also serve as predictive measures to determine the likelihood of successful mobility outcomes long-term (93). In an analysis comparing the association between balance, spasticity, contracture, muscle strength, gait profile scores to mobility outcomes post-injury (High-level Mobility Assessment Tool (HiMAT)(93)), ankle power generation at push off, and gait profile score accounted for 66.5% of the variability in mobility outcomes at a 6-month follow-up (93). These findings stress the importance of addressing gait integrity as it has a significant bearing on mobility outcomes post-injury.

In a description of the present literature, Williams et al. (59) documented the history of gait characterization post-TBI. This review helped to develop a taxonomic framework of TBI gait deviations. Williams et al. summary (59) noted that gait patterns after TBI were first characterized through detailed observational descriptions by researchers working as physical therapists but remained limited by a lack of quantifiable characteristics (78,85). Williams and co-authors (59) sought to build upon this previous work with the help of 3-dimensional gait analysis (3DGA). An updated classification system was developed by Williams and coauthors (59) who determined 6 defining features of gait impairment following TBI. Three of the classifications were associated with unilateral impairment: (1) spastic hemiparesis, (2) non-spastic hemiparesis, and (3) unilateral hemiparesis, and 3 were associated with bilateral impairments: (1) spastic bilateral paresis, (2) non-spastic bilateral paresis, and (3) ataxia/dyspraxia (59). The occurrence of unilateral and bilateral impairments between the sample of 126 individuals with gait disorders
following TBI was nearly equal, with 10 more individuals presenting with bilateral impairments (59).

Williams et al. (53) has previously discussed the methods which can be used to analyze gait post-TBI. To summarize, 3DGA appears to provide a wealth of information related to an individual's walking pattern from a kinematic, kinetic, and spatiotemporal perspective. However, it requires specialized staff to administer and a clinical setting that provides sufficient time to conduct the detailed assessment (95). Observational gait analysis (OGA) is often used in clinical practice but has limited accuracy in describing gait cycle patterns (53). A middle ground between OGA and 3DGA lies in the spatiotemporal characterization of gait. Williams et al. (53) ultimately concluded that the collection of spatiotemporal parameters is inexpensive and can accomplished easily in a clinical setting without limiting the accuracy or reliability of the outcome measures (96–99).

### 1.3 Spatiotemporal gait parameters

Spatiotemporal gait analysis encapsulates many distinct, yet interrelated features of the walking cycle, including forward progression (variables: velocity, stride/step length, cadence), dynamic stability (variables: step length variability, step time variability, step width variability, step width), and symmetry (variables: step length ratio, step time ratio). In a review, Kraan et al. (100) provided an insightful summary of spatiotemporal gait outcomes, their interconnectedness, and link to neurological impairment. Additionally, spatiotemporal variables have recently been associated with reductions in subcortical gray matter volume in pediatric TBI research (48). However, reporting on spatiotemporal variables does not come without limitations. As Williams et al. (75) noted, many biomechanical differences between individuals recovering from a TBI could result in similar spatiotemporal outcomes such as a reduced walking speed (57,66), thereby limiting the impact these findings could potentially have in physical therapy planning.

#### 1.3.1 Forward progression

In TBI gait-related research, the most reported spatiotemporal feature of gait is speed (75). Speed is highly correlated with cadence and stride length, particularly when increasing walking speeds with a TBI (56,57). People with severe TBI typically walk slower when compared to NT
individuals (57,62,63,66,68,70,93,101,102); however, this is not always the case (64,67,88,103).
Values of post-TBI preferred walking speed can range from 50 cm/s (56) to 152 cm/s (67). One example of a TBI and NT comparison at preferred and maximum walking speeds can be found in Niechwiej-Szwedo et al. (63). This analysis determined that 20 subjects receiving rehabilitation services for a TBI within the past 2 years had a preferred walking speed of 121 cm/s (SD=24), which was different from NT controls at 147 cm/s (SD=22) (63). In this same study, maximum velocity was different between patients with TBI (199 cm/s (SD=44)) and controls (235 cm/s (SD=0.24)) (63). However, Williams et al. (57) concluded that at maximum walking speeds there was no difference in velocity between individuals with TBI (164 cm/s (SD=37)) and NT controls (154 cm/s (SD=7)). In this study, Williams et al. (57) excluded 19 individuals from the analysis, as these individuals were not comfortable increasing walking speeds, and thus would have ultimately reduced the mean maximum walking speed for the TBI group.

Step and stride length measures are essential sub-components of speed generation (104). Thus, it is not surprising that Niechwiej-Szwedo et al. (63) found that the preferred step length of TBI patients (39 cm (SD=5)) (values normalized to height) was less than controls (45 cm (SD=4)). The same relationship existed at MP walking, as controls (55 cm (SD=3)) continued to demonstrate greater step lengths than TBI patients (47 cm (SD=5)) (63). Other studies (62,66,68,70) have also associated reductions in stride length (McFadyen (66): TBI = 150 cm; NT = 165 cm; Chou (68): TBI = 126.9 cm (SD=15.1); NT = 140.8 (SD=11.5)) with a reduction in preferred walking speed (McFadyen (67): TBI = 135 cm/s; NT =150 cm/s; Chou (68): TBI =151 cm/s (SD=16); NT = 130 cm/s (SD=10.9)) more so than a reduction in cadence (McFadyen (66): TBI ≥112 steps/min; NT ≥111 steps/min) (findings also found in (62,70)). Other studies with larger sample sizes have found a reduction in both step length (Ochi et al.(56) - (Males) more affected limb = 45 cm (SD=14), less affected limb = 36 cm (SD=16), (Females) more affected limb = 43 cm (SD=12), less affected limb = 38 cm (SD=13), NT: 78 cm (SD=6); and William et al. (57) - more affected limb = 61 cm (SD=15), less affected limb = 64 cm (SD=12)) and cadence (Ochi et al.(56) – (males) 67 steps/ min (SD=30), (females) 73 steps/min (SD=34), (controls) 117 step/min; and Williams et al. (32), 99.7 step/min (SD=14.61) to be associated with slower walking speeds.
Monitoring an individual’s ability to change gait speed from PP to MP walking or running is an informative predictor of community readiness and can identify underlying gait impairments that may not be evident during PP walking (57,63,72,105). In a cross-sectional study conducted by Williams et al. (57), not only were individuals with a TBI able to increase their walking speed to NT values at MP, but their cadence (122.28 steps/min (SD=15.6)) and step length (more affected: 79 cm (SD=13); less affected: 82 cm (SD=11)) values were also the same as controls under these conditions. At MP conditions, cadence and step length were associated with walking speeds for individuals with TBI, however, NT controls only demonstrated a correlation between cadence and MP walking speed (57). Although people with a TBI appear to demonstrate some distinguishing abnormalities in spatiotemporal measures of forward progression, it is also essential to evaluate other subcomponents of gait such as symmetry, variability, and motor-cognitive interference.

1.3.2 Gait variability

Walking is based on a repetitive stepping pattern. Thus, assessing the similarities or deviations between steps, based on features such as step time, step length, or step width provides an understanding of the consistency, rhythmicity, stability, and automaticity of an individual’s walking pattern (48,63,106–110). While consistency and stability are essential features of gait in order to navigate in a community setting, it is also essential that an individual has the ability to adapt and control their stepping pattern (111). The consistency and adaptability of gait can be indicated by the degree of step-to-step variability individuals display while walking. High step-to-step variability may be indicative of a system with reduced neuromotor control and impaired timing and balance (48,63,73,112,113). However, too much or little variability in the case of stride width has been shown to be predictive of falls, suggesting that an optimal level of variability may exist for some measures (111).

Compared to NT controls, individuals with TBI have a greater step length variability than controls during PP and MP walking (PP- TBI: ~3.5 %CV; controls ~2.5%CV; MP - TBI: ~4.5%CV; controls ~3%CV) (63). During PP walking, there was no noticeable difference in step time variability between those with a TBI (~3.5 %CV) and controls (~3.5 %CV) (63). This relationship changed during MP walking. People with TBI increased their step time variability
during fast walking (~4.5 %CV), while NT controls did not alter their level of step time variability to adjust speeds (~3.5 %CV) (63). Post-TBI step width variability was not different from controls under any conditions (PP - TBI: ~30%CV; controls ~25% %CV; MP – TBI: ~35%CV; controls: ~30%CV) but increased in both individuals with a TBI and controls during MP walking (a healthy adjustment in the gait pattern according to findings in older adults (114))(63). These values were similar to those reported by Inness and coauthors (39) for individuals following TBI: step length variability (PP: 4.6 %CV (SD=2.8); MP: 5.3 %CV (SD=4.39)), step width variability (PP: 29.0 %CV (SD=10.3); MP: 34.9 %CV (SD=14.2)) and step time variability (PP: 4.8 %CV (SD=3.20); MP: 7.1 %CV (SD=4.6)). Although not compared to NT values in the study, the values reported by Inness et al. (39) demonstrated greater step length variability, step time variability, and step width variability than control values reported by Niechwiej-Szwedo et al. (63) and Paterson et al. (76) for NT adults. A wider mean step width is often used by brain injured individuals to compensate for increased gait instability, but this can affect the timing of the harmonic mediolateral walking pattern as a result (58,75,98).

1.3.3 Gait symmetry
Symmetry variables evaluate side-to-side differences between limbs while walking and offer additional information about the gait cycle. Unilateral gait impairments have been shown to arise following TBI (3,56,59,77,79,116). Ochi et al. (56) determined that link between gait speed and asymmetry following TBI, as slow walkers are typically more asymmetric in temporal and spatial features. Chow et al. (77) conducted a study on 31 individuals with lower limb muscle hypertonia and an average gait speed of 53 cm/s. A difference was noted between more and less-affected limbs concerning spatiotemporal parameters such as step time, step cadence, foot velocity, and step length, with a greater swing time (%) and step length (cm) found on the more affected side (77).

Although gait analysis post-TBI is often done with the consideration of a more affected and less affected limb, it is rare to find reports of within-individual symmetry values (31). However, Wade et al. (31) reported a reduction in PP step length ratio from 0.94 to 1.00 between assessments at 2 and 6 weeks in an intervention-based study including 13 severely injured individuals. Hurt et al. (76) also reported on swing time symmetry post-TBI, noting that a cohort
of 8 subjects with gait impairments following TBI (age 30 years (SD=5); 4-24 months post-injury) had a swing time ratio of 1.3 (SD=0.2) during PP walking and 1.3 (SD=0.3) during MP walking. In addition to studying measures of forward progression, variability, and symmetry during PP and MP conditions, it is also essential to consider the effect of cognitive tasks while walking. The introduction of cognitive tasks while walking, via a dual-task paradigm, provides an indication of the automaticity of an individual’s gait pattern and may highlight underlying impairments that could go undetected during normal walking.

1.4 Cognitive motor interference

In an effort to further dual-task gait research following brain injury, McCulloch et al. (33) conducted a review detailing the current evidence regarding cognitive impairment following ABI and dual-task gait performance. To summarize, individuals post-TBI commonly present with cognitive impairments and motor tasks such as balance and walking may require more attention and are no longer automatic (38,81). This reduction in gait automaticity challenges limited available cognitive resources causing a reduction in dual-task gait performance. In a meta-analysis, Al-Yahya et al. (117) concluded that dual-task related changes in gait speed were the most sensitive and could distinguish between healthy individuals and those with neurological disorders as mild as concussions (118,119).

A few studies have assessed dual-task gait following severe TBI (67,81,120). Some studies have been conducted as a subset of greater acquired brain injury (ABI) related investigations (82). McFayden et al. (67) determined that a discrimination and decision-making task (Stroop audio and visual) caused a reduction of walking speed (TBI mean: ~149 cm/s) compared to single-task PP walking (TBI mean: ~152 cm/s), an observation that was not found in NT controls (TBI characteristics: n=11; age 37.6 years (SD=16.5); time since injury=2.8 months (SD=3)). However, the authors also noted that there was no difference between groupings (i.e., TBI or NT) for gait speeds under unobstructed dual-task or single speed conditions (67). In an examination of 24 individuals after TBI (age: 39.4 years (SD=13.3); time since injury: 117.8 months (SD=125.2)), McCulloch et al. (120) determined that the dual-task effect associated with the “Walking and Remembering Test” (a digit span test) was -20.9 (SD=13.0) for the motor component and -13.0 (SD=18.5) for the cognitive component. The most common reduction in
performance between the motor and cognitive dual-task effects was the motor-related effects (48% of sample) followed by both motor and cognitive effects (35% of sample). Measures of dual-task performance were not different between individuals who fell within the past 6 months and those who did not (120). Although specific dual-task effect values were not reported, Damiano et al. (121) noted that individuals with TBI (age: 31.3 years (SD=9.4), time post injury: >6 months) when compared with NT controls had greater motor and cognitive dual-task effects while walking and performing a word generation task.

1.5 Influence of individual and injury-related characteristics on gait

Predictors of independent mobility following TBI have been established. In a cohort of adults ranging in age after TBI, Katz et al. (27) determined that patients who achieved independent ambulation were typically younger, had better therapist assessed gait scores at admission, and tended to be less severely injured based on LPTA than those who did not ambulate. Injury severity and initial gait presentation attributed to a majority of the variance in ambulation outcomes following diffuse axonal injury (27). A duration of PTA >7 days has been associated with worse scores on the HiMAT used to assess balance and mobility problems post-TBI (122). In terms of walking speed, Ochi et al. (95) did not find any effects of age or sex grouping, yet demonstrated that time since injury provided insight into an individual’s gait impairment. Male and female individuals less than 1 year post-injury or male individuals more than 15 years post-injury had a reduced walking speed compared to those 5 to 10 years post-injury (56). McFadyen et al. (66) noted that LPTA was correlated with the level of toe clearance and gait speed of the lead limb during an obstacle avoidance task. Presently, the relationship between markers of injury severity (e.g., LPTA) and spatiotemporal measures remains unclear (31,123).

1.6 Longitudinal assessment of spatiotemporal measures of gait after TBI

1.6.1 Forward progression

Not only is it essential to understand spatiotemporal gait impairments post-TBI, but studying impairments over time can provide valuable information regarding neuroplasticity and rehabilitation-induced changes in walking ability and impairment. Wade et al. (31) noted that an increase in walking speed occurred early post-TBI. Whilst examining an acute gait and balance intervention, 13 individuals with a severe TBI (age: 25.2 years (SD=7.8); LPTA: 41.1 days
(SD=21.1)) participated in gait assessments that were conducted on 2 occasions, 2 to 6 weeks apart (time post-injury: 46.8 days (SD=27.7))(31). Over this time frame, walking speed significantly increased from 87 cm/s (SD=40) to 117 cm/s (SD=20) (31). In addition, Wade et al. (31) noted a change in stride length from 107 cm (SD=30) to 132 cm (SD=20). Williams et al. (93) performed repeated testing of mobility on 31 individuals, 8.7 months (SD=8.3) post-injury (age: 26.2 year (SD=9.6); LPTA: 60.8 days)), currently attending physiotherapy for mobility limitations. All individuals were able to walk without assistance over 20 meters and demonstrated a change in walking speed of 88 cm/s (SD=39) to 117 cm/s (SD=31) over the study time frame, which was deemed the result of increase ankle joint power generation during the push-off phase (93). Improvements in forward progression (i.e., velocity, cadence, and stride length) during spontaneous recovery was noted in a cohort of 14 children over a 5 month period after a severe TBI (124). These findings were echoed in a sample of 23 children with severe TBI over a 5 month period, approximately 3 months after injury (29). Velocity, stride length, and cadence all improved, with most of the change occurring within the first 2 months of follow-up (29). By the last assessment, most measures of forward progression were similar to those of the NT controls used in the study (29).

1.6.2 Variability

Using repeated clinical assessments throughout TBI recovery, Walker et al. (3) demonstrated that tandem gait, a measure of postural stability, remained abnormal for the longest portion of time when compared with other measures of motor recovery. More than a quarter of the sample of 102 severely injured patients (>1 day LPTA) continued to display abnormal findings 2 years after inpatient rehabilitation (3). The proportion of people with normal tandem gait at rehab, 6-months, 1 year, and 2 years post-injury was 26.7%, 67%, 69.3%, and 71.3%, respectively (3). Evidently this problem continues to exist for many individuals after TBI and reaches a plateau at the 6-month mark.

There have been few studies assessing the change in spatiotemporal variability after brain injury. Fifteen children were examined 1 year post-TBI and again 2 months later, and no reduction in step length variability occurred between assessments (28). Although this finding suggests no
change over time, in a more acute post-TBI population (time since injury: 2.8 months), a notable reduction in step length variability was observed between 5 month assessments (26).

1.6.3 Symmetry
Walker et al. (3) also demonstrated that hemiparetic gait (assessed by a clinician) improves for many individuals over time. The proportion of people with normal symmetry at rehab, 6-months, 1 year, and 2 years was 46.5%, 83.0%, 85.1%, 88%, respectively (3). A few studies have assessed changes in measures of symmetry in the context of intervention programs (76,77). Wade et al. (31) reported a significant change in step length ratio from 0.94 to 1.00 between assessments 2 to 6 weeks apart in 13 severely injured individuals. Similarly, after a 5-week RAS intervention, Hurt et al. (76) noted a non-significant improvement in swing time ratio during PP walking, from 1.3 to 1.2, and at MP walking, from 1.3 to 1.2, over the intervention period.

1.6.4 Dual-task effect
The only longitudinal assessment of dual-task gait following brain injury was conducted in a mixed cohort of individuals with TBI and stroke (82). Fifty individuals recovering after an array of brain injuries were assessed while walking and performing 1 of 4 cognitive tasks: (1) spoken word generation task, (2) mental arithmetic task, (3) verbal paired associate monitoring task, and (4) visuospatial decision task, and dual-task effects of -7%, -8%, -6% and -7% were found for stride time, respectively (42). While performing the same cognitive tasks and walking, NT controls did not show significant dual-task effects (82). Stride time and stride time variability were the only spatiotemporal variables reported in this study, however, no dual-task effect were observed for stride time variability (82).

Sixteen participants (time post-injury: 7 months) of the 50 studied above (time post injury: 16 months) who demonstrated substantial motor (n=14) or cognitive (n=2) dual-task effects were reassessed longitudinally (181 days (SD=81) between assessments) (42). For spoken word generation and paired association tasks, the dual-task effect did not significantly change, however, the dual-task effect associated with visuospatial decision making was significantly reduced (42). In terms of change in cognitive dual-task performance, there was no significant change over time (82). In an elliptical intervention study, Damiano et al. (121) demonstrated that
motor and cognitive dual-task effects for a word generation and serial subtraction task did not change after an 8-week intervention time period (dual-task effect values not reported).

In conclusion, mobility impairments following TBI can restrict community engagement (65,86,125,126). As such, identifying gait impairments from a spatiotemporal perspective with specific focus on how these features change longitudinally will enable clinicians and patients to refine gait interventions, thereby ameliorating walking impairments and improving quality of life.

1.7 Traumatic brain injury rehabilitation and gait interventions
A number of systematic reviews have documented the present state of gait rehabilitation interventions after mild to severe TBI (19–23). Presently, no pharmacological interventions exist to address motor impairments following TBI (35). As a result, rehabilitation is the only available tool to provide treatment. Specific gait interventions often differ between therapists and institutions (21,23). In a 2011 review, a total of 20 studies evaluated outcomes of physical therapy interventions focused on gait and balance after TBI (19). Only 6 studies evaluated interventions using spatiotemporal gait outcomes (31,76,97,127–129). To build on this review, a similar search was conducted and updated to the year 2018 (121,130–136). For the purpose of this thesis only gait interventions that assessed spatiotemporal outcomes, both those from the review in 2011 and those retrieved in this present thesis, will be discussed.

1.7.1 Functional electrical stimulation interventions
In 1989, Bogataj et al. (127) demonstrated that after a 2 to 3-week training program with functional electrical stimulation (FES), an improvement in velocity, stride width, and step length symmetry was documented (n=1). In 2014, Leung et al. (111) performed a comparison between a 6-week multimodal treatment program (combining tilt table standing, splitting and electrical stimulation) and a single modality treatment program (tilt table standing alone) for a group of individuals post-TBI who could not ambulate more than 17 meters without physical assistance. At the end of both interventions, there was no between-group difference in walking speeds at 6 and 10 week follow-ups. Other FES interventions have assessed the effectiveness of this tool as a gait intervention for individuals following an ABI, thus individuals with TBI were often included.
in the sample but were a small minority (154). Lairamore et al. (131) demonstrated that there was no difference in gait speed outcomes following 45 minutes of FES or sensory stimulation (3 times per week), however this finding was attributed to improvements noted in both treatment groups.

### 1.7.2 Treadmill and elliptical training interventions

In a randomized controlled trial (RCT), Brown et al. (97) assessed the effectiveness of 2 forms of treadmill training in a group of individuals with gait asymmetry (based on PT observation) and the ability to walk for 20 minutes regardless of the need of assistance. Individuals were randomized to receive either 3 months of body-weight supported treadmill training (BWSTT) (n=10) and physical therapy or conventional over ground training (COGT) (n=9) and physical therapy (sessions 2 times per week for 14 weeks, 15 minutes of walking per session) (97). There were no group differences in post-intervention changes in walking speed (COGT: 39.2 cm/s (SD=34) to 42 cm/s (SD=32.5), BWSTT: 32 cm/s (SD=22.2) to 32.8 cm/s (SD=24.1)) and stride width (COGT: 18.1 cm (SD=6.6) to 14.5 cm (SD=6.2), BWSTT: 18.1 cm (SD=6.0) to 17.1 cm (SD=4.7), and both groups continued to walk slower and with a wider stride width than NT adults (men: 8 cm (138), women: 6.9 cm (139))(97). There was a significant difference in post-intervention changes in symmetry (step length differential) after the two interventions (COGT: 19.7 cm (SD=17.8) to 12.4 cm (SD=13.2), BWSTT: 16.1 cm (SD=19.1) to 25 cm (SD=25.6)), as BWSTT appeared to increase asymmetry by 8.9 cm while the COGT group improved with a decrease in asymmetry of 7.3 cm (53). In addition, in a separate smaller study, one week of treadmill training increased speed, cadence, and step length for two individuals with chronic TBI and ataxia (129). Building upon previous efforts related to BWSTT, Esquenazi et al. (132) performed a randomized comparative study on participants who were able to ambulate at PP velocities of 20 cm/s to 60 cm/s post-TBI. Individuals were allocated to either receive manual assisted (n=8) or robotic-assisted BWSTT (n=8) (18 sessions over 6 to 8 week period, 45 minutes of walking per session) (132). PP walking speed (35 cm/s to 53 cm/s) and PP step length symmetry (2.9 to 1.8) significantly improved in the robotic group, while MP walking speed (61 cm/s to 80 cm/s) and walking endurance measured by the 6MWT increased in the manually assisted group (132). Neither intervention arm demonstrated an improvement in single limb support time ratio and no between-group differences post-training were observed (108). The
translatability of these present findings to individuals with a higher mobility status post-TBI may be limited.

Buster et al. (140) concluded that training with an elliptical can produce similar movement patterns to walking and encourage beneficial variability of movement patterns without progressing to overly disorganized trajectories. Damiano et al. (121) built upon these previous findings by implementing an 8-week home-based rapid-resisted elliptical training program (5 days per week for 8 weeks, 30 mins per session) for 12 independently ambulating individuals with a TBI and no patient report of instability or history of falling. Assessments were conducted before and after exercise training and at an 8-week follow-up, during which participants were no longer exercising (121). Although there was a difference in motor and cognitive dual-task effects between individuals with a TBI and NT controls for a word generation task, there were no improvements in motor or cognitive dual-task effects (for either word generation and counting backwards) or any spatiotemporal measures of gait (121).

1.7.3 Conventional rehabilitation techniques

In 1997, Wade et al. (31) demonstrated that between assessments 2 to 6 weeks apart, gait and balance training (based on a motor learning model for rehabilitation by Carr et al. (141)) combined with conventional physical therapy, increased the velocity (87 cm/s (SD=40) to 117 cm/s (SD=20)), stride length (107 cm (SD=30) to 132 cm (SD=20)), step length (R: 55 cm (SD=20) to 66.1 (SD=10) cm; L: 52 cm (SD=20) to 66 cm (SD=10)) and step length ratio (0.94 to 1.00) of 13 individuals with a severe TBI. Williams et al. (88) performed an assessment of a rehabilitation training program designed to focus on task-specific or ballistic strength training, in order to optimize muscle function for walking. Patients received 1-2 centre-based therapy sessions per week and performed either a home-based or gym-based program 3-4 times per week (64). Thirty-five individuals (age: 28.4 years) with an LPTA of 67.6 days (SD=49.5) and an average time post-injury of 25.6 months (SD=53.9) demonstrated an improvement in PP velocity from 95 cm/s (SD=19) to 122 cm/s (SD=22) over a 6-month training period (88). Before beginning the strength intervention, the positive work and average power generation during stance phase by the ankle was reduced in TBI participants compared to NT controls (88). As compensation for reduced proportional power generation from the ankle an increase in hip power
generation was noted (88). After 6 months of training, however, there was no difference in TBI and NT individuals in terms of the proportional contribution from each of the lower limb joints to total power generation (88).

Two studies assessed the benefit of intensive mobility/exercise training on adults with chronic severe TBI (133,134). Peters et al. (133) demonstrated that intensive training (150 min/session, 20 sessions, 5 days/week for 4 weeks) comprised of 3 distinct domains of activities: (1) gait training with body weight supported treadmill training, (2) balance activities, and (3) strength, coordination and range of motion exercises, increased MP walking velocity on the 10-m walk test beyond the minimal detectable change (>5 cm/seconds) in 8 out of 10 participants (133). Furthermore, 6 of 10 individuals exceeded the minimal detectable change for the 6-minute walk test (>36 m) and the Timed Up and Go test (>2.9 seconds).

In 2016, Charrette et al. (134) conducted a pilot study using an intensive training intervention. The intervention aimed for 50-80% of maximum heart rate for 60-90 minutes using exercises such as: (1) treadmill walking with and without body weight support, (2) stationary biking, (3) over ground waking, (4) stairs and step-ups, (5) obstacle courses, (6) strength exercises, (7) stretching exercises, and (8) balance exercises (134). The intensive training intervention caused improvements in walking speed based on the 10-m walk test and walking endurance measured by the 6MWT for both low and high ambulatory individuals (134).

1.7.4 Dual-Task Interventions
Evans et al. (142) has assessed the effect of dual-task training on gait after TBI. Individuals with ABI and evidence of performance of at least 1 SD below the mean on the divided attention and dual-tasking test battery, as well as reporting dual-task difficulties in everyday life, were included in the study (142). Participants were randomized to receive either a 30-minute session of dual-task training 1 time per week for 5 weeks, as well as at-home practice for 2 practice sessions per day, 5 days a week (age: 44.4 years, TBI: n=7, stroke: n=2, tumor: n=1, time post injury: 59 months) or a null control group that only involved phone calls from study personnel to check-in (age=45.11 years, TBI: n=5, stoke: n=4, time post injury: 115.6 months) (142). The dual-task training included walking while: (1) listening to instrumental music, (2) listening to
vocal music, (3) listening to a recording of talk-based radio and then answering recorded questions, (4) completing a verbal fluency task, and (5) answering autobiographical questions (142). There was no significant group or time effects during single-task gait performance or single-task cognitive performance following dual-task training (142). However, a difference in dual-task gait speed was reported between those who underwent dual-task training and those who did not (142).

1.7.5 Rhythmic auditory stimulation (RAS)
Hurt et al. (76) conducted a 5-week home-based RAS intervention on 5 individuals with chronic gait impairments following TBI. Each subject was set up on a 5-week gait therapy program in which individuals walked at home for an allotted number of minutes to rhythmically accented music tapes set to individualized normal and fast tempo (76). After the intervention, velocity significantly increased (63.9 cm/s (SD=26.8) to 96.06 cm/s (SD=44.4)(+50% change)), as did cadence (85.7 steps/min (SD=26.6) to 98.3 steps/min (SD=29.1)(+15% change)), and stride length (89 cm (SD=22) to 113.8 cm (SD=28)(+29% change)) (76). Swing time symmetry improved from 1.3 (SD=0.2) to 1.2 (SD=0.3) and began to better approximate a ratio of 1:1, however, it did not demonstrate a statistically significant change (-12% change) over the intervention period (76). Under fast walking conditions, there were no statistically significant increases from pre-test to post-test in velocity (108.7 cm/s to 137.1 cm/s, +33% change), cadence (108.5 steps/min to 112.1 steps/min, +2% change), stride length (115.4 cm to 128.5 cm, +18% change) and swing time symmetry (1.3 to 1.2, 13% decrease) (76). This preliminary study was followed by a dissertation by Wilfong et al. (125), which also demonstrated an improvement in velocity, stride length, and cadence in a group of 7 individuals post-TBI.

To build upon previous efforts using RAS in neurologic populations, Kim et al. (135) used a 4-week randomized control trial to compare RAS and conventional physiotherapy in 12 adolescents post-ABI. Significant group differences were observed from pre-test to post-test in velocity (RAS: 93 cm/s (SD=27) to 116 cm/s (SD=19), control: 97 cm/s (SD=27) to 98 cm/s (SD=14), cadence (RAS: 111.8 steps/min (SD=9.04) to 122.9 cm/s (SD=10.2), control: 112.51 cm/s (SD=10.17) to 112.91 cm/s (SD=4.8) and step time (RAS: 0.54 s to 0.48 s; controls: 0.52 s to 0.55 s), but not step length, step width, or single and double support percentages (135).
was also a group difference in changes in range of motion of the hip and knee, with a greater increase observed in the RAS intervention group (135).

In conclusion, the number of gait intervention studies that assess spatiotemporal variables other than walking speed is fairly limited. In general, improving measures of forward progression appears to be feasible using a variety of gait intervention tools. Improving symmetry, both temporally and spatially appears to be less studied and more difficult to accomplish. Similarly, improving step-to-step variability does not appear to be a focus of any of the present interventions and dual-task effects are only emerging as a focus of TBI gait interventions. Ultimately, it is important to assess the effectiveness of these interventions on an array of spatiotemporal outcomes to determine which intervention is most suitable to address specific gait impairments post-TBI.

1.8 Gait rehabilitation and rhythmic auditory stimulation

Music has proven to be an effective method of improving neuromotor abnormalities arising from neurodegenerative diseases and acquired neurological injuries (76,144–146). When an individual loses the ability to generate coordinated motor movements, the temporal features embedded in music can provide a framework to optimize neuromotor circuitry (147). As an individual performs a motor movement with an accompanying external auditory cue (e.g., metronome), the timing information that is easily decoded and processed in auditory neural pathways can project to related motor areas in a process called oscillatory neural resonance (148–152).

In the past few decades, research efforts have explored the therapeutic benefits of auditory-motor synchronization on repetitive patterned movements such as walking (144,153,154). The effect of RAS has been used as both single-session experiments and as multi-session training studies. Single-session studies are often interested in the immediate ability to entrain footstep to the auditory cueing, while multi-session training intervention studies are interested in the spatiotemporal change training with a cue can induce during uncued walking. For the purpose of this thesis, we will be discussing the effects of multi-session training interventions, as we will be investigating the effects of RAS on uncued walking.
1.8.1 Rhythmic auditory stimulation and Parkinson’s Disease

A loss of neuromotor timing is a common cause of gait impairments for individuals with PD and as a result many studies have used external auditory cues as a mechanism of PD gait restoration (155–162). Parkinsonian gait is characterized spatiotemporally by a reduced velocity and stride length and an increased cadence and stride-to-stride variability (163). A recent meta-analysis (144) assessed the use of RAS as a gait training tool in PD. Overall, the studies collectively demonstrated that training with RAS can increase walking speed, step length, and reduce cadence for individuals with PD (144). In terms of training dosage, the meta-analysis concluded that treatment should be limited to 25 to 45 minutes in duration for a minimum of 3 to 5 sessions per week and should include tempo variation of ±10% (144). This was deemed ideal as it limited the negative physical and mental ramifications of overtraining (i.e., fatigue) (164). Furthermore, Wittwer et al. (165) noted that RAS has proven to be an effective gait rehabilitation tool in PD, citing its role as a standard component of clinical practice (163,166–168).

While the effects of RAS on measures associated with forward progression (i.e., velocity, cadence, and stride length) are relatively well established, the effects on step-to-step variability have not been analyzed as systematically. In a study conducted in 21 individuals with idiopathic PD, Dalla Bella et al. (169) concluded that 12 sessions of RAS over the span of 1 month was sufficient to significantly reduce stride time variability post-training. This finding was similar to those reported by del Olmo et al. (170), as 1 hour motor training sessions with rhythmic sounds 5 times per week, for 4 weeks, reduced step time variability during PP walking.

A meta-analysis by Ghai et al. (144) noted that RAS has been used to improve dual-task performance in PD patients in a few studies. Of these studies, five explored the application of RAS training regimes to improve dual-task walking for individuals with PD (160,170–173). After 13 weeks of training for 30 minutes, 3 times per week, de Bruin et al. (173) noted that individuals who were randomized to the RAS group, compared to controls, increased speed and cadence while walking with an added cognitive dual-task (serial subtractions). Another study by del Olmo et al. (170) reported improvements in velocity, step length, and cadence (though not statistically significant) while walking with a motor dual-task, following 4 weeks of daily 1 hour RAS training sessions. A few successive studies by another author group, however, found that
training over a 3-week period to auditory, and in some cases spatiotemporal cueing (i.e., “take a big step in time with the music”), significantly increased cued and non-cued walking speed and step amplitude during a motor-dual task (171,172). By comparison to the evidence surrounding single-task walking, Ghai et al. (144) noted that dual-task performance following RAS has not been studied as systematically in the PD population, often limited by differences in cueing delivery and dual-task paradigm between studies.

1.8.2 Rhythmic auditory stimulation (RAS) and other neurological populations

In addition to PD, RAS has been used as a gait intervention in other neurological patient populations, such as post-stroke (153), multiple sclerosis (174), dementia (175) and cerebral palsy (154). A systematic review has evaluated the use of RAS in neurological populations other than PD from both the perspective of immediate entrainment and as a long-term gait intervention (165). These RAS training studies reported on velocity, stride/step length, cadence, swing time ratio, and variability using RAS (165). Two recent meta-analyses concluded that between groups post-stroke receiving RAS or a control intervention, there was a mean difference of 15.3 cm/s, 16.1 steps/min, 16.9 cm, and 15% post-intervention for velocity, cadence, stride length, and symmetry, respectively (203,159). In addition to this strong evidence surrounding measures of forward progression and symmetry post-stroke, preliminarily evidence also suggests that temporal variability post-stroke may be influenced by RAS (178).

By comparison to the present state of RAS research in the field of stroke and PD, less is known about the application of RAS in TBI. As previously discussed in the TBI gait training portion of the introduction, Hurt et al. (76) conducted a non-controlled study of 5 adults with TBI and noted an increase in PP velocity, stride length, and cadence post-RAS intervention. These findings were explored further in a dissertation by Wilfong et al. (143). After a 3-week RAS intervention, individuals with a TBI experienced an increase in velocity, stride length, and cadence (143). Finally, Kim et al. (135) employed a 4-week RCT to compare RAS and conventional physiotherapy in 12 adolescents post-ABI. Group differences were noted in velocity, cadence, and step time, but not in step length, step width, or single and double support percentages (135). A group difference in changes in hip and knee range of motion were also greater in the group receiving RAS (135).
When investigating gait rehabilitation interventions for the purpose of advancing clinical practice, there are other important criteria to evaluate in addition to the effects of RAS on gait. The additional benefits of RAS have been summarized extensively by Ghai et al. (144,146). Most notably these benefits include a high participant satisfaction (204), improved motivation to complete motor tasks (181), ease of integration with conventional gait program in a rehabilitation and home-based setting (76), additional psychosocial benefits (182,183) and improved cognitive functioning while training with music (184).

1.9 Summary
Each year 6,000 Canadians become permanently disabled as a result of a TBI and 500,000 people in Ontario alone are living with a brain injury (185). Research indicates that post-TBI gait and mobility remains an issue for many individuals long-term and these issues are linked to community integration and quality of life (65,85,86,126). Mobility impairments have previously been described by observation (78), kinematic and kinetic outcome measures (57–59,93), and spatiotemporal parameters (56,62,63,75). Common spatiotemporal gait impairments include reduced speed, cadence, stride length (56), and asymmetry (31,76), as well as increased step-to-step variability (63) and dual-task effect (66,81,120). One aspect of gait that has been understudied is the change in spatiotemporal gait variables over time. To date, TBI gait studies have not systematically assessed longitudinal change in spatiotemporal gait parameters during the first-year post-injury. Furthermore, the influence of injury severity on gait recovery is poorly understood, particularly in relation to gait recovery early post-TBI. Characterizing spatiotemporal gait changes over the first-year post injury will ideally provide insight into potential avenues therapists and patients can explore to optimize rehabilitation interventions.

RAS as a gait training technique has been underutilized in the TBI population. The intervention has been shown to address many of the gait issues that are common in the TBI population, such as impaired forward progression, variability, symmetry, and dual-tasking ability (134,143). To date, only 2 studies have assessed the benefits of RAS in adults with TBI (76,143) and 1 study has examined its application in children and adolescents with ABI (135). It is essential to further examine the feasibility of this gait training technique, as this gait training tool could benefit a number of individuals with mobility impairments after TBI.
2 Study 1: Examining change in spatiotemporal measures of gait in the first 12-months following traumatic brain injury

Abstract

Background: Gait deficits after TBI include reduced gait speed, asymmetry, increased step-to-step variability, and difficulty dual-tasking. Changes in these properties of gait in the first year post-TBI have not been characterized to date. A comprehensive understanding of longitudinal patterns of spatiotemporal gait post-TBI and their relation to meaningful measures of community integration will help design and refine gait interventions that will ultimately positively impact mobility after brain injury.

Methods: A secondary analysis was performed on a database containing results from over-ground gait assessments of 100 people admitted to an inpatient rehabilitation program. Spatiotemporal parameters of PP, MP, and dual-task gait were collected. Outcome variables of interest included velocity, cadence, step length, step width, swing time ratio, step length ratio, step length/time/width variability, and walk-ratio. A determination of cognitive-motor interference was undertaken by comparing dual-task velocity with single-task velocity to determine the dual-task effect. Individuals were grouped by LPTA as follows: 1-7 days, 1-4 weeks, and >4 weeks. Individuals were included in the analysis if they had a LPTA >1 day, completed 2 of 3 assessments, had no orthopedic injuries, and did not require a gait aid to complete their walking trial. A mixed model was used to examine the effect of LPTA grouping and time on the gait variables of interest after controlling for sex and age. Post-hoc Tukey testing was used to compare pairwise difference between groups and time points. Spatiotemporal parameters at 12-months post-injury were then compared to a sample of NT individuals to determine which features of gait remained atypical after 1 year of recovery. Finally, spatiotemporal measures at 2, 5, and 12 months were correlated, both concurrently and predictively, with total and sub-scale scores of the CIQ administered at 5, 12, and 24 months post-injury. Multiple comparisons were controlled for with the Bonferroni-Holm adjustment.

Result: A total of 62 individuals with TBI met inclusion criteria for the current secondary analysis (mean age: 39.5 years (SD=17.6) (16 females: 46 males)). There were 11, 36, and 15 individuals classified with LPTA of 1-7 days, 1-4 weeks, and >4 weeks, respectively. Measures
of forward progression (velocity (PP: p=.003, MP: p=.002), cadence (PP: p=.006, MP: p<.0001) and step length (PP: p=.046) significantly improved over the first year post-TBI, while measures of step-to-step variability did not change in the same time frame. Swing time symmetry also improved over time (PP: p=.003, MP: p=.0026), while the dual-task effect of velocity diminished (p=.0087). Under fast walking conditions severity group differences were identified for measures of velocity (p=.01) and step length (p=.004). Step length variability (PP: p=.005, MP: p=.02), step time variability (PP: p=.003, MP: p=.03), swing time symmetry (PP: p=.0001, MP: p=.005), and step width (PP: p=.005, MP: p=.0337) also appeared to differ between severity groupings regardless of walking condition. Individuals with the most severe brain injuries had the greatest number spatiotemporal differences in gait by comparison to the other injury severity groups. The group with an LPTA duration of 1-7 days (p=.006) had a reduced cadence compared to NT controls. The least and most severely injured groups had elevated walk ratio values compared to NT values (1-7 days, p=.009; >4 weeks, p=.006). By 1 year post-injury, groups with an LPTA 1-4 weeks (p=.0004) and >4 weeks (p=.0005) had greater PP step time variability than controls. Groups with an LPTA of 1-4 weeks (p=.004) and >4 weeks (p=.002) had a wider step width than controls. All LPTA groups displayed more difficulty dual-tasking compared to NT controls. The most severely injured group had a PP swing time ratio that was higher than NT controls (p=.006). Finally, PP step time variability (r=-.46, p=.001) and MP step width (r=-.63, p=.0005) at 5 months were negatively correlated with CIQ total scores at 5 months and 24 months post-injury, respectively. Step width at 12 months post-injury while walking at PP (r=-.66, p=.0003) and MP (r=-.59, p=.001) was associated with CIQ home sub-scale and total scores at 24 months post-injury, respectively.

**Discussion:** Spatiotemporal gait demonstrated improvement in measures of forward progression after brain injury. However, many features related to stability, symmetry, automaticity, and efficiency remained different than NT values by 1 year post-injury. Walking condition (i.e., PP or MP) appeared to determine differences in gait performance between severity groups. Gait interventions proven to address gait automaticity, stability, and efficiency should be explored in this population with the ultimate intention of improving long-term community integration.
2.1 Introduction

Locomotion following a TBI can be impaired as a result of limitations to neuromotor and cognitive function. Motor disorders and their recovery have been well described following TBI (35). As many studies have described, although independent gait is restored post-TBI (24,27), it often remains slow, asymmetric, and not autonomous (48,56–59,61–66,68,69,73,75,77,78,81,93,101). In addition to, or perhaps a cause of, reduced walking speed, many individuals also report instability and compensations for instability while walking (48,57,58,62–68,72). Difficulty achieving a balance between motor and cognitive performance while walking (i.e., dual-tasking) is another common problem post-TBI (62,33,78,172). Reduced walking speed and increased dynamic instability can have a direct impact on a patient’s quality-of-life. Walking speed (85) and complex mobility (65,126,186) impairments have been correlated with an individual's ability to integrate into their community following brain injury.

A substantial body of evidence has detailed the specific impairments in gait after TBI, yet how these impairments recover, or plateau and fail to improve, following injury has been sparsely documented. Longitudinal studies in the past have often focused on changes in clinical measures of gait (3). From this perspective, research has shown that dynamic instability and asymmetric walking patterns, if present at 6 months, appear to persist well into the first and second year after injury (3). Few studies have characterized spatiotemporal measures longitudinally, but research indicates that these features of walking are subject to change over the course of an individual’s time post-injury (56). In a separate study assessing an acute gait intervention, velocity, step/stride length, and step length symmetry changed significantly between assessments at 2 and 3 months after severe TBI (31). A significant change in step length variability, but not step width variability or step width was observed over a 5-month assessment period in a sample of children in the first months following severe TBI (29). Finally, studies in acquired brain injury have noted a greater improvement in single-task motor and cognitive performance than measures of dual-task performance post-injury (82). The current literature on longitudinal change in spatiotemporal gait over the first year following adult TBI remains limited by small sample sizes (31), varying follow up time points (56), and a limited number of spatiotemporal variables. Previously, longitudinal investigations have assessed velocity, cadence, stride length, or spatial symmetry, but not step-to-step variability, dual-task effect on velocity, temporal symmetry, step width, or walk ratio (31,56).
Studies have detailed patient-specific or injury-related characteristics that influence longitudinal change in motor function after TBI (27,122). In previous research, LPTA, a marker of injury severity, has been used as a predictive measure of recovery outcomes following TBI (14,15). Specifically, after adjusting for covariates such as age and cause of injury, individuals with a longer duration of PTA were less likely to have a "good recovery" than individuals with a shorter duration of PTA at 1-year post-injury, based on the Glasgow Outcome Scale (15). No study to date has assessed change in spatiotemporal gait characteristics longitudinally based on injury severity.

Finally, studies correlating spatiotemporal properties of gait to measures of community integration (e.g., CIQ (221)) are typically limited to single assessment time points (86) and a narrow range of spatiotemporal variables (i.e., velocity only) (125). Recently measures of high-level mobility such as the Community Balance and Mobility Scale (CB&M) (188) have been compared, concurrently and predictively, with community integration outcomes (30). This study found that multi-task components of the CB&M had a stronger association with community integration even as late as 2 years post-injury (30).

The objectives of this present study were: (1) to evaluate change in spatiotemporal measures of gait based on severity classification over the first year post-TBI; (2) to determine if there is a difference in spatiotemporal variables at 1 year post-injury when compared to NT controls; (3) to assess the relationship between spatiotemporal measures over the first-year post-injury and measures of community integration (i.e., CIQ (187)). We hypothesized that over the first-year post-injury an improvement in forward progression (i.e., velocity, cadence, and step length), instability (i.e., step-to-step variability and step width), walking efficiency (i.e., walk ratio), and gait automaticity (i.e., dual-task performance) would occur. As the literature dictates, motor recovery occurs early post-injury (3,27); thus we anticipated that most of these measures would demonstrate change between the first 2 assessments. Furthermore, we expected the most severely injured individuals, according to LPTA, to exhibit the highest degree of initial impairment in gait measures and the slowest pattern of recovery. At 12 months post-injury, we hypothesized that measures of walking stability, symmetry, efficiency, and dual-task performance would present
with more abnormalities compared to NT values than measures of forward progression. Lastly, we anticipated that measures of instability, symmetry, and dual-task performance would have stronger concurrent and predictive correlations with community integration outcomes than measures of forward progression.

2.2 Methods
This study is a secondary analysis of data from a longitudinal parent study that followed people over the first 24 months following a TBI.

2.2.1 Participants for original study
The parent study aimed to investigate the natural course of cognitive and motor recovery in patients referred to the inpatient, neurorehabilitation program located at the Toronto Rehabilitation Institute. The inclusion criteria for this study were as follows: (1) acute care diagnosis of TBI, (2) PTA of >1 hour/or GCS score of ≤12 at emergency admission or the scene of accident and/or positive computed tomography or magnetic resonance imaging findings, (3) age between 18 and 80 years, (4) able to follow simple commands in English based on speech language pathologist intake assessment, and (5) competency to provide informed consent for study or availability of legal decision-maker. Exclusion criteria included: (1) concurrent diagnosis of diseases primarily or frequently affecting the central nervous system, ascertained via medical records and/or screening of family members for patients over 60 years regarding any definite or possible prior diagnosis of dementia; (3) history of psychotic disorder; and, (4) TBI secondary to other brain injury (e.g., fall caused by a stroke).

2.2.2 Participants included in secondary analysis
The following were the additional inclusion criteria for the current secondary analysis: (1) a LPTA >1 day; (2) the ability to walk independently (i.e., no gait aid) for at least 2 of the 3 total assessment time points. Spatiotemporal variables were not analyzed if the individual was limited to walking exclusively with the support of a walking aid for all assessments. If an individual presented with an orthopedic injury at a particular assessment time point, those spatiotemporal measures were removed from the study for the single assessment time point where the injury was present. In some cases, orthopedic injuries occurred at the same time as the brain injury, while
other individuals had orthopedic injuries arise later in the study duration from other causes. The purpose of this study was to examine centrally mediated gait changes; however, orthopedic injuries can alter spatiotemporal properties of gait that may alter the intended study aims. After restricting LPTA to durations longer than 1 day, only individuals who fell into the classification of severe, very severe, and extremely severe classification in accordance with 1-7 days, 1-4 weeks, and >4 weeks duration of PTA were included (18). LPTA is known to be associated with motor recovery post-TBI (14,15,17,27,66,186), and this exclusion criterion allowed us to focus on individuals who had sustained a severe TBI, which has been the focus of gait research efforts in the past. Furthermore, there was a limited number of individuals in the parent study with a moderate TBI making the comparison with this severity classification less feasible.

2.2.3 Testing protocol for original study
Once an individual consented to participate in the study a cognitive and motor battery was administered at 2, 5, and 12 months following TBI. Other assessments such as the CIQ were completed at a 2-year follow-up assessment. Of the 62 individuals included in the present analysis, the 2-month evaluation occurred on average 68.1 (SD=26.3) (range=18-149) days post-injury. The 5-month assessment took place on average 155.9 (SD=32.9) (range=121-311) days post-injury. The 12-month assessment took place on average 392.1 (SD=41) (range=329-527) days post-injury.

2.2.4 Measures
Demographic variables
Information concerning age, sex, LPTA, and acute care length of stay (ACLOS) were abstracted from the hospital medical records when available. LPTA was typically assessed in acute-care and in the in-patient neurorehabilitation program using the Galveston Orientation and Amnesia Test (GOAT) (189). The GOAT evaluates recent and distant memories and when an individual scored higher than 75 on two consecutive trials, at least 24 hours apart, then the period of post-traumatic amnesia was considered finished (189). If LPTA was not accessible in the medical record, a member of the parent study team questioned the patient and caregivers with a structured interview to determine LPTA. The duration of post-traumatic amnesia was classified by an ordinal scale employed by Lezak et al. (18) where 1 represents a LPTA <5 minutes, 2 represents
a LPTA between 5-60 minutes, 3 represents a LPTA 1-24 hours, 4 represents a LPTA 1-7 days, 5 represents a LPTA 1-4 weeks, and 6 represents a LPTA > 4 weeks (18). ACLOS, in days, was calculated based on admission and discharge dates from the acute care hospital.

**Community Integration Questionnaire scores**

The CIQ was administered at 5, 12, and 24 months post-injury. The CIQ is used to assess participation in the community after TBI via a self-reported questionnaire consisting of a series of 15 questions related to returning to roles at home, in the workforce, and society (190). Three sub-scales comprise the CIQ: home, social, and productive, with a higher score reflecting better integration. The home integration sub-scale concerns an individual's ability to independently fulfill roles and responsibilities of the domestic nature. An individual's ability to participate in recreational activities and availability of social support systems are assessed on the social integration sub-scale. Lastly, the productivity sub-scale assesses aspects of return to work, school, and volunteer capacities after TBI. Scores between 0 to 29 can be obtained, and the sub-scale scores range from 0-10 (home), 0-12 (social) and 0-7 (productivity). The CIQ scale has been shown to be a reliable, valid, and sensitive measure in the TBI population (187,190–192).

**Overground gait assessment**

Spatial and temporal parameters of gait were recorded using a pressure sensitive mat (GAITRite, CIR Systems INC., Clifton, NJ), a reliable and valid method of measuring gait (193). The mat measured 4.6 m long and 0.9 m wide. The instrument possesses a spatial resolution of 1.27 cm and a temporal resolution ranging from 80-120 Hz. Subjects walked over the mat at least 3 times while wearing self-selected footwear. To assure gait parameters were collected during steady-state walking, reducing gait variability associated with starting and stopping, participants were asked to begin walking 2.5 meters from the mat (194). The inspection and cleaning of gait data occurred at the end of each walking trial to remove any half-footprints or incorrectly detected footfalls. Participants walked under the following conditions: (1) PP, (2) MP, and (3) dual-task. The dual-task selected for this investigation was serial subtractions, which has previously been used in neurological populations (195–197). Cognitive responses while performing the dual-task walk were not reported uniformly between participants; as such, only spatiotemporal effects of dual-task performance will be discussed in the present study.
**Spatiotemporal variables of interest**

Spatiotemporal variables of interest included velocity (cm/s), cadence (steps/min), step length (cm), step width (cm), step time variability (%CV), step length variability (%CV), step width variability (%CV), walk ratio (step length (cm)/cadence (steps/min)), swing time ratio (larger swing time/smaller swing time), and step length ratio (larger step length/smaller step length). Dual-task effect (%) is a measure of cognitive-motor performance compared to single-task motor performance. The formula for calculating dual-task effect on velocity is: dual-task effect (%) = \((\text{dual-task velocity} - \text{single-task velocity})/\text{single-task velocity})\times100. A larger negative value is indicative of a greater dual-task effect due to a greater difference in velocity between single-task and dual-task walking conditions. Velocity was used as a marker of change between single-task and dual-task conditions because it was shown to be the most sensitive measure of change in TBI populations (64).

The GAITRite system calculates velocity automatically by dividing the distance traveled by the ambulation time. Step length is a measure of the heel centre of the current footprint to the heel centre of the previous footprint of the opposite foot. Step width is measured from the midline midpoint of the existing footprint to the midline midpoint of the previous footprint of the opposite foot. Step time is the time elapsed from the first contact of one foot to the first contact of the opposite foot. Swing time is initiated with toe off and ends with heel strike. It is defined as the time elapsed between the last contact of the current footfall to the first contact of the next footfall on the same foot. Individual footfall data for each pass on the GAITRite mat were extracted and measures of swing time ratio and step length ratio as well as step time/length/width variability were calculated in a created Matlab program. Swing time ratio and step length ratio were calculated as a ratio of left and right swing time and step length values, respectively - with the larger value in the numerator according to recommendations by Patterson et al. (198). Variability in the gait pattern was examined using the coefficient of variation (%CV, where \(CV=\text{standard deviation/mean} \times 100\)). The coefficient of variation is a measure of relative step-to-step variability and was calculated for each participant during each walking trial (199).
2.2.5 Statistical analysis

Objective 1: To evaluate the change in spatiotemporal measures of gait based on severity classification over the first year post-TBI.

Bilateral differences between limbs for each walking condition were compared using a paired t-test for measures including step length, step width and swing time. No significant differences were found between the right and left limbs; thus, step length, step time, and step width for both limbs were averaged and used for subsequent analyses. Normality of variables were assessed according to the Shapiro-Wilk test. Any variables not normally distributed were log transformed. Measures of variability, symmetry, and step width were all log-transformed (63). A linear mixed model was used to determine the main effects of injury severity classification (3 LPTA classifications: 1-7 days, 1-4 weeks, and >4 weeks) and time (3 assessments: 2, 5, and 12 months) for each gait variable of interest (Proc Mixed SAS 9.3(200)). A Banded Toeplitz with two bands covariance structure to account for the repeated measurements within the participants. Due to the unequal distribution between assessment time points, autoregressive of order 1 was not appropriate (37). Lund’s test of residuals was used to determine outliers in each of the spatiotemporal models (202). Outliers were removed from the analysis to ensure the assumptions of the parametric tests were met. Age and sex were controlled for in each mixed model. Sex and age both influence spatiotemporal measures of gait (203) and age can dictate recovery after TBI (17,204). Thus, to analyze the effect of injury severity on recovery over time, these patient-specific factors were taken into consideration. If the primary effect of severity or time was significant (p<0.05), post-hoc Tukey testing was performed to compare between specific time points and severity groupings to determine pairwise differences. This model also assessed any interaction effect between the severity classification and assessment time. If Tukey adjusted p-values were significant (p<0.05), raw p-values were reported.

Objective 2: To determine if there is a difference in spatiotemporal variables at 12 months post-injury when compared to a sample of NT controls.

All spatiotemporal measures from objective 1 at 12 months post-injury, were compared with age-matched NT controls. Measures of step-to-step variability were again log transformed, while
values of gait symmetry were rank transformed to meet the assumptions of the parametric tests. A linear mixed model was used to compare values between LPTA groupings at 12 months and NT controls (Proc MIXED SAS 9.3 (200)). Post-hoc Tukey testing was used to investigate pairwise comparisons. Age and sex were controlled for in each mixed model. Sex and age both influence spatiotemporal measures of gait (203). Thus, to analyze the effect of injury severity on recovery at 12-months post-injury, these patient-specific factors were taken into consideration. Lund's test of residuals was used to determine outliers in each of the spatiotemporal variables (202). A one-way ANOVA was used to determine if there was any difference in age (204) between the controls and individuals with TBI. A Fisher's exact test was conducted to determine if there was a sex imbalance between LPTA groups and NT controls.

**Objective 3:** To study the relationship between spatiotemporal gait measures and community integration during the first year post-TBI.

This study was also interested in determining the relationship between spatiotemporal measures of gait at 2, 5, and 12 months post-injury and scores on the CIQ at 5, 12, and 24 months post-injury (187). Zero-order Spearman rank and third-order partial correlations (controlling for age (205), sex (187,190,206,207), and injury severity (14,36,208,209)) were used to assess the relationship between values of spatiotemporal gait at 2, 5, and 12 months post-injury and CIQ scores at 5, 12, and 24 months post-injury. Differences between males and females in community integration have noted that women typically score higher on aspects related to home and social integration (187,210). Similarly, age influences community reintegration, as teenagers display higher scores on social and productive elements of reintegration while greater home integration is noted for adults aged 30 to 59 (210). We also controlled for injury severity as it can influence community integration (211,212). Both concurrent (i.e., 5 months spatiotemporal gait and 5 months CIQ) and predictive (i.e., 5 months spatiotemporal gait and 12 months CIQ) comparisons between spatiotemporal measures of gait and community integration outcomes were conducted. The Bonferroni-Holm correction was used to account for multiple comparisons. A moderate relationship had a correlation coefficient of r=.30-.50 and a strong correlation had a coefficient r ≥.50 (213).
2.3 Results

2.3.1 Participant characteristics

The database from the original study contained data from 100 participants. Sixty-two participants were included in the analysis with a mean age of 39.5 years (SD=17.5, range: 18-76). The demographic information for study participants can be found in Tables 2.1 and 2.2. Reasons for exclusion from the secondary analysis and corresponding numbers of individuals were: only one measurement time point (n=23), use of a gait aid during all walking trials (n=2), missing LPTA values (n=7), and orthopedic injuries for 2 or more of the assessments (n=6). Of the 62 participants included, 46 (74%) of the participants were male. Between the 3 LPTA groups, 11, 36, and 15 individuals were divided into the groupings 1-7 days, 1-4 weeks, and > 4 weeks, respectively. Specific characteristics of each LPTA grouping are displayed in Table 2.2. A Fisher's exact test confirmed that there was no difference in sex between the 3 LPTA groupings (p=.31). A 1-way ANOVA confirmed that there was no difference in age between the 3 LPTA groups (F_{2,59}=0.01, p=.9, \eta^2 =.0004), but a difference in ACLOS existed (F_{2,59}=4.3, p=.02, \eta^2 =.13). At 2, 5, and 12 months, individuals scored an average of 55.8 (SD=22), 69.0 (SD=19.3), and 72.8 (SD=16.7), respectively, on the CB&M (maximum possible score=96).

Table 2.1 – Distribution of participants between gender, LPTA classification, and assessment completion pattern. Units reported as mean (SD) or number (%).

<table>
<thead>
<tr>
<th>Category</th>
<th>Mean (SD) or Number (%) n=62</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>39.5 (17.7)</td>
</tr>
<tr>
<td>Acute Care Length of Stay (days)</td>
<td>31.7 (18.8)</td>
</tr>
<tr>
<td>Completed all 3 assessments (2-12 months)</td>
<td>43 (69%)</td>
</tr>
<tr>
<td>Completed first 2 assessments (2-5 months)</td>
<td>7 (11%)</td>
</tr>
<tr>
<td>Completed last 2 assessments (5-12 months)</td>
<td>10 (16%)</td>
</tr>
<tr>
<td>Completed first and last assessment (2 &amp; 12 months)</td>
<td>2 (1%)</td>
</tr>
<tr>
<td>Males</td>
<td>46 (74%)</td>
</tr>
<tr>
<td>Female</td>
<td>16 (26%)</td>
</tr>
<tr>
<td>Length of Post-Traumatic Amnesia (1-7 days)</td>
<td>11 (18%)</td>
</tr>
<tr>
<td>Length of Post-Traumatic Amnesia (1-4 weeks)</td>
<td>36 (58%)</td>
</tr>
<tr>
<td>Length of Post-Traumatic Amnesia (&gt;4 weeks)</td>
<td>15 (24%)</td>
</tr>
</tbody>
</table>
Table 2.2 – Distribution of participants based on LPTA severity grouping. Units reported as mean (SD) or number (%).

<table>
<thead>
<tr>
<th>Length of Post-Traumatic Amnesia (LPTA)</th>
<th>1-7 days</th>
<th>1-4 weeks</th>
<th>&gt;4 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td># of participants</td>
<td>11 (18%)</td>
<td>36 (58%)</td>
<td>15 (24%)</td>
</tr>
<tr>
<td># of males</td>
<td>9 (82%)</td>
<td>24 (66%)</td>
<td>13 (87%)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>38.8 (18.6)</td>
<td>39.5 (18.3)</td>
<td>39.4 (16.3)</td>
</tr>
<tr>
<td>Acute care length of stay (days)</td>
<td>25.6 (16.5)</td>
<td>28.7 (14.3)</td>
<td>43.2 (25.1)</td>
</tr>
<tr>
<td>Completed all 3 assessments (2-12 months)</td>
<td>9 (81%)</td>
<td>23 (64%)</td>
<td>11 (73%)</td>
</tr>
<tr>
<td>Completed first 2 assessments (2-5 months)</td>
<td>0</td>
<td>6 (16%)</td>
<td>1</td>
</tr>
<tr>
<td>Completed last 2 assessments (5-12 months)</td>
<td>1 (9%)</td>
<td>7 (19%)</td>
<td>2 (13%)</td>
</tr>
<tr>
<td>Completed first and last assessment (2 &amp; 12 months)</td>
<td>1 (9%)</td>
<td>0</td>
<td>1 (7%)</td>
</tr>
</tbody>
</table>

2.3.2 Objective 1: Longitudinal change in spatiotemporal measures of gait over the first-year post-injury

Forward progression

*Time:* Results from the model of time and injury severity for spatiotemporal measures of forward progression for PP and MP gait are reported in Table 2.3 and 2.4, respectively. At PP walking conditions, a main effect for time was identified for measures of velocity ($F_{2,109}=6.0$, $p=.003$, $η^2_p=.06$) (Figure 1a), cadence ($F_{2,111}=5.4$, $p=.006$, $η^2_p=.06$) (Figure 1b), and step length ($F_{2,117}=3.16$, $p=.046$, $η^2_p=.04$) (Figure 1c). Post-hoc testing revealed that between months 2 and 5, an increase occurred in velocity ($p=.0007$), cadence ($p=.001$), and step length ($p=.01$), while an increase in velocity ($p=.006$) and cadence ($p=.02$) were also noted between 2 and 12 months. No increase occurred between 2 and 12 months for step length as the least severely injured group decreased in step length between 5 and 12 months. At MP conditions, a main effect for time was identified as velocity ($F_{2,110}=6.7$, $p=.002$, $η^2_p=.07$) (Figure 2a) and cadence ($F_{2,105}=11.2$, $p<.0001$, $η^2_p=.06$) (Figure 2b) increased over the first year. Post-hoc testing revealed that between months 2 and 5, as well as months 2 and 12 post-injury, an increase in velocity (2-5 months: $p=.0004$, 2-12 months: $p=.02$) and cadence (2-5 months: $p<.0001$, 2-12 months: $p=.005$) transpired. No significant pattern of change was noted for MP step length over time (Figure 2c). The severity groups appeared to vary in direction of change, as some increased step length (i.e., most severely injured individuals) and others decreased step length over the course of recovery (i.e., least severely injured individuals).
Walk ratio is a summary measure of gait that provides an indication of walking stability, efficiency, timing, and automaticity. An optimal walk ratio value is .65 cm/(steps/min) and in healthy adults has been found to be .67 cm/(steps/min) (SD=.07) while walking on a level surface (214). Due to the independence of walk ratio and speed, changes in gait related to stability, efficiency, timing, and automaticity can be gauged independently of speed, thereby providing additional insight into distinct components of neuromotor control. There was no main effect of time on walk ratio during either walking condition. Visual inspection indicates varying patterns of change, with groups increasing, decreasing, or remaining unchanged over time for this measure.

**Injury Severity:** There was no difference between severity groupings for measures of forward progression during PP walking conditions. However, while walking at maximum speed, group differences were noted in velocity ($F_{2,110}=6.7$, $p=.002$, $\eta^2=.05$) and step length ($F_{2,117}=3.2$, $p=.05$, $\eta^2=.08$). Upon further inspection, post-hoc tests revealed the most severely injured group had a slower walking speed than the least severely injured group ($p=.0027$). The most severely injured group had a reduced step length compared to the groups with an LPTA of 1-7 days ($p=.002$) and 1-4 weeks ($p=.01$). Finally, no group differences in walk ratio were displayed at either walking speed.

*Table 2.3 - All significant effects of time and severity for PP walking.*

<table>
<thead>
<tr>
<th>Measure</th>
<th>Main Effect</th>
<th>Post-hoc</th>
</tr>
</thead>
</table>
| Velocity      | Time: $F_{2,109}=6.0$, $p=.003$, $\eta^2=.06$ | 2-5 months, $p=.0007$  
2-12 months, $p=.006$ |
| Cadence       | Time: $F_{2,111}=5.4$, $p=.006$, $\eta^2=.06$ | 2-5 months, $p=.001$  
2-12 months, $p=.02$ |
| Step Length   | Time: $F_{2,117}=3.2$, $p=.046$, $\eta^2=.04$ | 2-5 months, $p=.01$ |
**Figure 2.1** – Change in PP a) velocity, b) cadence and c) step length in the first year following TBI. Blue = LPTA 1-7 days, red = LPTA 1-4 weeks, and green = LPTA >4 weeks.

**Table 2.4** - All significant effects of time and severity for MP walking.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Main Effects</th>
<th>Post-Hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>Time: $F_{2,110}=6.7$, $p=.002$, $\eta^2_p=.07$</td>
<td>2-5 months, $p=.0004$</td>
</tr>
<tr>
<td></td>
<td>LPTA: $F_{2,103}=4.8$, $p=.01$, $\eta^2_p=.05$</td>
<td>1-7 days &amp; &gt;4 weeks, $p=.003$</td>
</tr>
<tr>
<td>Cadence</td>
<td>Time: $F_{2,105}=11.2$, $p&lt;.0001$, $\eta^2_p=.06$</td>
<td>2-5 months, $p&lt;.0001$</td>
</tr>
<tr>
<td></td>
<td>LPTA: $F_{2,103}=5.8$, $p=.004$, $\eta^2_p=.08$</td>
<td>1-7 days &amp; &gt;4 weeks, $p=.002$</td>
</tr>
<tr>
<td>Step Length</td>
<td>LPTA: $F_{2,103}=5.8$, $p=.004$, $\eta^2_p=.08$</td>
<td>1-4 weeks &amp; &gt;4 weeks, $p=.0113$</td>
</tr>
</tbody>
</table>
**Figure 2.2** – Change in MP a) velocity, b) cadence and c) step length in the first year following TBI. Blue = LPTA 1-7 days, red = LPTA 1-4 weeks, and green = LPTA >4 weeks.

### Variability, Symmetry and Step Width

**Time:** The results from the model of time and injury severity for measures of step-to-step variability, symmetry, and step width for PP and MP can be found in Tables 2.5 and 2.6, respectively. A main effect of time was noted for swing time ratio during both PP ($F_{2,113}=6.1$, $p=.003, \eta^2_p=.07$) (Figure 4c) and MP conditions ($F_{2,107}=6.3$, $p=.003, \eta^2_p=.07$) (Figure 5d). Post-hoc testing revealed that a decrease occurred between 2 and 5 months ($p=.003$) as well as 2 and 12 months ($p=.003$). No change in measures of step-to-step variability, step length symmetry, and step width occurred over time.

**Injury Severity:** A significant main effect of injury severity was noted for step length variability (LPTA: $F_{2,96.2}=5.6$, $p=.005, \eta^2_p=.06$) (Figure 4a), step time variability (LPTA: $F_{2,95.5}=6.1$, $p=.003, \eta^2_p=.07$) (Figure 4b), swing time ratio (LPTA: $F_{2,95.5}=6.1$, $p=.003, \eta^2_p=.07$) (Figure 4c), and step width (LPTA: $F_{2,106}=5.5$, $p=.005, \eta^2_p=.06$) (Figure 4d) during PP walking. Post-hoc testing revealed a difference between groups with an LPTA of 1-7 days and 1-4 weeks compared to the group with an LPTA of >4 weeks for step length variability ($p=.003, p=.006$), step time variability ($p=.002, p=.006$), swing time ratio ($p<.0001, p=.0007$), and step width ($p=.005$, $p=.001$).
p=.004). During MP walking, the main effect of injury severity was noted for step length variability (F_{2,89.6}=4.2, p=.02, \eta^2_p=.05) (Figure 5a), step time variability (F_{2,90.3}=3.8, p=.03, \eta^2_p=.04) (Figure 5b), step length ratio (F_{2,81.3}=5.3, p=.007, \eta^2_p=.06) (Figure 5c), swing time ratio (F_{2,107}=6.3, p=.003, \eta^2_p=.07) (Figure 5d), and step width (F_{2,99.9}=3.5, p=.03, \eta^2_p=.05) (Figure 5e). Post-hoc testing revealed a difference between individuals with an LPTA of 1-4 weeks and >4 weeks in step time variability (p=.008) and step length variability (p=.007). The most severely injured group also had a step length ratio and swing time ratio that were larger than groups with a PTA duration of 1-7 days (p=.009, p=.002) and 1-4 weeks (p=.004, p=.01). The most severely injured group had step width values that were significantly larger than the least severely injured group (p=.01).

**Figure 2.3** – Change in dual-task effect of velocity

**Dual-Task Effect on Velocity**

There was an effect of time (F_{2,99.1}=4.9, p=.009, \eta^2_p=.06) on the dual-task effect on velocity. Thus, as time since injury increased, the relative difference in dual-task walking speed compared to single-task walking speed increased in magnitude, causing a more negative dual-task effect. Post-hoc testing revealed that a difference occurred between 2 and 5 months (p=.004) and 2 and 12 months (p=.007).

**Table 2.5** – All significant effects of time and severity for PP walking.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Main Effect</th>
<th>Post-hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Length Variability</td>
<td>LPTA: F_{2,96.2}=5.6, p=.005, \eta^2_p=.06</td>
<td>1-7 days &amp; &gt;4 weeks, p=.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-4 weeks &amp; &gt;4 weeks, p=.006</td>
</tr>
<tr>
<td>Step Time Variability</td>
<td>LPTA: F_{2,95.5}=6.1, p=.003, \eta^2_p=.07</td>
<td>1-7 days &amp; &gt;4 weeks, p=.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-4 weeks &amp; &gt;4 weeks, p=.006</td>
</tr>
<tr>
<td>Swing Time Ratio</td>
<td>Time: F_{2,113}=6.1, p=.003, \eta^2_p=.07</td>
<td>2-5 months, p=.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-12 months, p=.003</td>
</tr>
<tr>
<td></td>
<td>LPTA: F_{2,80.9}=9.9, p=.0001, \eta^2_p=.1</td>
<td>1-7 days &amp; &gt;4 weeks, p=.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-4 weeks &amp; &gt;4 weeks, p=.0007</td>
</tr>
<tr>
<td>Step Width</td>
<td>LPTA: F_{2,106}=5.5, p=.005, \eta^2_p=.06</td>
<td>1-7 days &amp; &gt;4 weeks, p=.005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-4 weeks &amp; &gt;4 weeks, p=.004</td>
</tr>
</tbody>
</table>
Figure 2.4 – Change in PP a) step length variability, b) step time variability, c) swing time ratio, and d) step width in the first year following TBI. Blue = LPTA 1-7 days, red = LPTA 1-4 weeks, and green = LPTA >4 weeks.
Table 2.6 – All significant effects of time and severity for MP walking.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Main Effect</th>
<th>Post-hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Length Variability</td>
<td>LPTA: $F_{2,89.6}=4.2$, $p=.02$, $\eta^2=.05$</td>
<td>1-4 weeks &amp; &gt;4 weeks, $p=.007$</td>
</tr>
<tr>
<td>Step Time Variability</td>
<td>LPTA: $F_{2,90.3}=3.8$, $p=.03$, $\eta^2=.04$</td>
<td>1-4 weeks &amp; &gt;4 weeks, $p=.008$</td>
</tr>
<tr>
<td>Swing Time Ratio</td>
<td>Time: $F_{2,107}=6.3$, $p=.003$, $\eta^2=.07$</td>
<td>2-5 months, $p=.0009$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-12 months, $p=.006$</td>
</tr>
<tr>
<td></td>
<td>LPTA: $F_{2,85}=5.7$, $p=.005$, $\eta^2=.07$</td>
<td>1-7 days &amp; &gt;4 weeks, $p=.002$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-4 weeks &amp; &gt;4 weeks, $p=.01$</td>
</tr>
<tr>
<td>Step Length Ratio</td>
<td>LPTA: $F_{2,81.3}=5.3$, $p=.007$, $\eta^2=.06$</td>
<td>1-7 days &amp; &gt;4 weeks, $p=.009$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-4 weeks &amp; &gt;4 weeks, $p=.004$</td>
</tr>
<tr>
<td>Step Width</td>
<td>LPTA: $F_{2,99.9}=3.5$, $p=.03$, $\eta^2=.05$</td>
<td>1-7 days &amp; &gt;4 weeks, $p=.01$</td>
</tr>
</tbody>
</table>

Figure 2.5 – Change in MP a) step length variability, b) step time variability, c) swing time ratio, d) step length ratio, and e) step width in the first year following TBI. Blue = LPTA 1-7 days, red = LPTA 1-4 weeks, and green = LPTA >4 weeks.
Table 2.7 – Summary of spatiotemporal change over time and between-group differences.

<table>
<thead>
<tr>
<th>Walking Condition</th>
<th>Across Time Comparison</th>
<th>Severity Group Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 and 5 months</td>
<td>1-7d &amp; &gt;4wks &amp;</td>
</tr>
<tr>
<td>Preferred Pace</td>
<td>2 and 12 months</td>
<td>1-4wks &amp; &gt;4wks</td>
</tr>
<tr>
<td>velocity</td>
<td>velocity</td>
<td>step length variability</td>
</tr>
<tr>
<td>cadence</td>
<td>cadence</td>
<td>step time variability</td>
</tr>
<tr>
<td>step length</td>
<td>swing time ratio</td>
<td>swing time ratio</td>
</tr>
<tr>
<td>swing time ratio</td>
<td></td>
<td>step width</td>
</tr>
<tr>
<td>Maximum Pace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>velocity</td>
<td>velocity</td>
<td>step length variability</td>
</tr>
<tr>
<td>cadence</td>
<td>cadence</td>
<td>step time variability</td>
</tr>
<tr>
<td>swing time ratio</td>
<td>swing time ratio</td>
<td>swing time ratio</td>
</tr>
<tr>
<td>swing time ratio</td>
<td></td>
<td>step width</td>
</tr>
<tr>
<td>Dual-task effect</td>
<td>dual-task effect</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.9. There was a group difference in PP cadence ($F_{3.36.9}=4.5, p=.009, \eta_p^2=.14$), PP step time variability ($F_{3.33.9}=6.5, p=.001, \eta_p^2=.19$), PP walk ratio ($F_{3.32.9}=5.2, p=.004, \eta_p^2=.16$), PP swing time ratio ($F_{3.29.6}=3.6, p=.002, \eta_p^2=.12$), MP step width ($F_{3.21.4}=4.7, p=.01, \eta_p^2=.17$) and dual-task effect of velocity ($(F_{3.34.9}=8.4, p=.0003, \eta_p^2=.23$). The least severely injured group had a PP cadence that was lower than NT controls ($p=.0006$). The 2 most severely injured groups had a PP step time variability that was higher than controls (LPTA 1-4 weeks: $p=.0004$, LPTA >4 weeks: $p=.005$). PP walk ratio values were higher for LPTA groups with the shortest ($p=.009$) and longest duration of PTA ($p=.006$) when compared with NT controls. PP swing time ratio was higher for individuals in the group with a LPTA >4 weeks compared to NT controls ($p=.004$). All LPTA groups had a dual-task effect on velocity that was greater than controls (1-7 days: $p=.003$, 1-4 weeks: $p=.0002$, >4 weeks: $p=.0004$). The following measures did not differ between all LPTA groups and controls: velocity (PP/MP), cadence (MP), step length (PP/MP), walk ratio (MP), step length variability (PP/MP), step time variability (MP), step width variability (PP/MP), swing time symmetry (MP), and step length ratio (PP/MP).

**Table 2.8** – Summary of significant findings from the comparison between LPTA groups at 12 months and neurotypical controls.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Condition</th>
<th>LPTA Group</th>
<th>Mean (SD)</th>
<th>NT mean (SD)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadence</td>
<td>Preferred Pace</td>
<td>1-7 days</td>
<td>104.4 (9.8)</td>
<td>115.8 (8.9)</td>
<td>$p=.006$</td>
</tr>
<tr>
<td>Walk Ratio</td>
<td>Preferred Pace</td>
<td>1-7 days</td>
<td>.70 (.1)</td>
<td>.58 (.06)</td>
<td>$p=.009$</td>
</tr>
<tr>
<td>Step Time Variability</td>
<td>Preferred Pace</td>
<td>1-4 weeks</td>
<td>3.9 (1.3)</td>
<td>3.1 (1.1)</td>
<td>$p=.0004$</td>
</tr>
<tr>
<td>Swing Time Ratio</td>
<td>Preferred Pace</td>
<td>&gt;4 weeks</td>
<td>1.05 (.04)</td>
<td>1.01 (.02)</td>
<td>$p=.006$</td>
</tr>
<tr>
<td>Step Width</td>
<td>Maximum Pace</td>
<td>1-4 weeks</td>
<td>10.8 (2.9)</td>
<td>8.5 (2.5)</td>
<td>$p=.004$</td>
</tr>
<tr>
<td>Dual Task Cost</td>
<td>1-7 days</td>
<td>-14.7% (13.1)</td>
<td>-1% (8)</td>
<td>$p=.003$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-4 weeks</td>
<td>-10.7% (14.1)</td>
<td></td>
<td>$p=.0002$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;4 weeks</td>
<td>-10.7% (6.9)</td>
<td></td>
<td>$p=.0004$</td>
<td></td>
</tr>
</tbody>
</table>
Objective 3: To assess the relationship between spatiotemporal measures over the first-year post-injury and community integration outcomes.

Gait measures at 2, 5, and 12 months were correlated with CIQ total and sub-scale scores at 5, 12, and 24 months, both concurrently and predictively (for CIQ scores see Table 2.10). A summary of all findings from the zero-order and third-order partial correlations can be found in Table 2.11. There were no correlations between gait measures at 2 months and CIQ scores at 5, 12, and 24 months post-injury. PP step time variability at 5 months demonstrated a moderate negative correlation with CIQ total scores at 5 months after controlling for age, sex, and injury severity (r= -.46, p=.001) (Figure 2.6a). MP step width at 5 months demonstrated a strong negative correlation with CIQ total scores at 2 years after controlling for age, sex, and injury severity (r= -.63, p=.0005) (Figure 2.6b). PP step width at 12 months exhibited a strong negative correlation with CIQ home scores at 2 years after controlling for age, sex, and injury severity (r= -.66, p=.0003) (Figure 2.7a). Finally, MP step width at 1 year post-injury displayed a strong negative correlation with CIQ total scores at 2 years after controlling for age, sex, and injury severity (r= -.59, p=.001) (Figure 2.7b).

Table 2.9 – Summary of CIQ scores by assessment time point. (Mean (SD)).

<table>
<thead>
<tr>
<th>Variable Total</th>
<th>5 Months</th>
<th>12 Months</th>
<th>24 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIQ Home</td>
<td>3.4 (2.5)</td>
<td>3.4 (2.2)</td>
<td>3.8 (1.7)</td>
</tr>
<tr>
<td>CIQ Social</td>
<td>7.8 (2.3)</td>
<td>7.8 (2.5)</td>
<td>7.0 (2.4)</td>
</tr>
<tr>
<td>CIQ Productivity</td>
<td>2.4 (1.6)</td>
<td>3.3 (1.8)</td>
<td>4.2 (2.2)</td>
</tr>
<tr>
<td>CIQ Total</td>
<td>13.6 (5)</td>
<td>14.4 (4.9)</td>
<td>14.9 (4)</td>
</tr>
</tbody>
</table>

Table 2.10 – Summary of correlation analysis.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Condition</th>
<th>Variable</th>
<th>Zero-Order</th>
<th>Third-Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 months gait -</td>
<td>PP (n=51)</td>
<td>STV &amp; Total</td>
<td>r= -.41, p=.003</td>
<td>r= -.46, p=.001</td>
</tr>
<tr>
<td>5 months CIQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 months gait -</td>
<td>MP (n=29)</td>
<td>SW &amp; Total</td>
<td>r= -.55, p=.002</td>
<td>r= -.63, p=.0005</td>
</tr>
<tr>
<td>24 months CIQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 months gait-</td>
<td>PP (n=29)</td>
<td>SW &amp; Home</td>
<td>r= -.45 p=.02</td>
<td>r= -.66, p=.0003</td>
</tr>
<tr>
<td>24 months CIQ</td>
<td>MP (n=29)</td>
<td>SW &amp; Total</td>
<td>r= -.54, p=.002</td>
<td>r= -.59, p=.001</td>
</tr>
</tbody>
</table>
2.4 Discussion
Within the first 5 months post-injury, an improvement in measures of forward progression occurred. Velocity, cadence, and step length all increased during PP walking. All improvements were retained at 12 months, with exception of PP step length. The 2 least severely injured groups displayed a reduction in PP step length between 5 and 12-month assessments which contributed to the undetectable difference when baseline step length values were compared to measures at 1 year. This pattern of improved forward progression early post-injury aligns with studies that have detailed acute changes in forward progression following TBI (31,93). Williams et al. (93) noted a
mean improvement of 29 cm/s in PP velocity over a 6-month period that began on average 8.7 months post-injury (LPTA: 60.8 days (SD=32.8)). The mean increase observed in Williams et al. (93) is most representative of the magnitude of change exhibited by the most severely injured group in the current analysis (23.8 cm/s). Injury severity demonstrated an effect on forward progression, however this relationship only existed when individuals were tasked with walking at maximum speeds. Group differences were noted in MP velocity and step length, but no relationship was noted between groups in MP cadence. The difference in MP forward progression was noted between the most and least severely injured LPTA groups. As time since injury progressed, the most severely injured group demonstrated an increase in MP step length and velocity, while the least severely injured group displayed a steady decrease in MP step length and velocity. This divergent pattern of change between groups contributed to the significant difference noted for injury severity for this particular spatiotemporal variable. By 12 months, both groups appeared to achieve a MP step length that resembled those of their NT counterparts.

The findings in the present analysis demonstrate that the time it takes to achieve NT walking speed varies based on walking condition. The most severely injured group exhibited sub-NT PP walking speeds at the 2-month assessment, yet at the same assessment, this group could walk at NT MP speeds (215). The restoration of MP walking speed could serve as a predictive marker for the eventual return to NT PP walking speeds. Williams et al. (57) noted that individuals with LPTA >4 weeks in duration walked with reduced preferred walking speeds, but could increase walking speeds to the same degree as their NT counterparts. The distinction between individuals with a TBI and NT controls in Williams et al. (57) study was noted in the kinematic, kinetic, and spatiotemporal changes required to increase speed from PP to MP walking, not the MP walking speed itself.

At no point over the course of recovery did any LPTA group demonstrate a PP cadence within the range of NT individuals (215). In a large sample of participants post-TBI (n=41) (LPTA: >4 weeks), a reduced cadence during PP walking was a more commonly reported gait abnormality than reduced step length (58). The authors speculated that reducing cadence was an adaptation made by individuals following brain injury to compensate for increased gait instability (58). In
the present study, a reduced cadence may provide reasoning for elevated levels of gait variability and disruption of gait cycle timing. Though our present study only identified 1 LPTA group with a reduced PP cadence at 1 year post-injury compared to the sample NT controls, it is worth noting that according to age-matched reference values reported by Oberg et al. (215) all groups were below the age-matched 95% confidence limit throughout the course of recovery.

There was no clear pattern of change in walk ratio over time or distinctions between severity groups. At 12 months post-injury, both the least and most severely injured groups had elevated walk ratios compared to NT controls. While statistically significant, these findings may not be clinically significant as both LPTA groups had walk ratio values that resembled previously reported NT values (107,214,216). Thus, future comparisons with larger sample sizes will be required to clarify the distinction between LPTA groups and NT controls. This finding related to walk ratio, along with a reduced PP cadence, provides valuable insight into TBI gait prioritization strategies. NT adults walking on uneven surfaces, adapted to the increased external instability by selecting a higher walk ratio compared to level surface walking (214). The authors described this adaptation as the prioritization of gait stability over efficiency, which may provide an explanation for the presentation of post-TBI gait in the current study (214).

These findings related to forward progression suggest that rehabilitation services appear to effectively address the restoration of walking speed following TBI. The restoration of NT walking speed may take longer for individuals with a greater degree of initial impairment resulting from a more severe brain injury, but by 1 year post TBI, walking speed on average is restored. Although these findings may not be representative of individuals of all mobility levels following TBI, it does provide an indication that the restoration of lower limb power generation and power distribution may be addressed as a result of conventional gait, strength, and balance interventions (88). The findings surrounding forward progression also highlight a potential shortcoming of post-injury speed restoration. At 12 months post-injury, all groups appeared reliant on a PP step length that was larger than the upper 95% confidence limit of NT reference values and a reduced cadence to achieve desired walking speed (215). This imbalance in step length and cadence can reduce gait timing, stability, automaticity, and energy transfer between steps (107,108,216). Perhaps greater emphasis should be placed on increasing step frequency.
throughout rehabilitation to ensure that the restoration of walking speed post-TBI occurs with an optimal step length to frequency proportion.

Step time, step length, and step width variability did not demonstrate a significant pattern of change over time. Measures of variability often show linear or quadratic relationships with measures of forward progression (107,108,217), thus as an individual migrates towards an optimal speed, stride length, cadence, and walk ratio in the recovery process, a concurrent change in step-to-step variability should be expected. In pediatric TBI literature, patterns of change in step length variability have demonstrated mixed results. Between assessments at 1 year post-injury and 2 months following, no differences in step length variability occurred (28). However, in a more acute post-TBI pediatric sample (time since injury: 2.8 months), a notable change in step length variability was observed over a span of 5 months. (29). In contrast to the reduction in step length variability, no change in step width variability was demonstrated over the 5-month assessment period, although step width variability at baseline was larger than NT controls (29). In a single assessment study, Niechwiej-Szewdo et al. (63) demonstrated that adults post-TBI possessed elevated step length variability during PP and MP walking and higher step time variability during MP walking only.

In the present study, all LPTA groups demonstrated varying patterns of change in step time variability and step length variability. A main effect of injury severity was found for both of these spatiotemporal measures. The least severely injured group achieved near NT values for PP step time variability and step length variability by the first assessment and retained these values at the 12-month assessment. The more severely injured groups (i.e., LPTA 1-4 weeks and >4 weeks) demonstrated higher baseline PP step-to-step variability and at the 12-month assessment displayed PP step time variability values above those of the sample NT population. Although this is the first study to report on longitudinal change in step-to-step variability in adults over the first year post-TBI, we have some prior understanding of how stability recovers over time. Walker et al. (3) demonstrated that the tandem gait, a measure of instability, remained abnormal for many individuals 2 years after injury. More than a quarter of the sample of 102 individuals with severe TBI (>1-day LPTA) continued to display abnormal findings 2 years after inpatient rehabilitation and the group exhibited a distinct plateau in recovery of this clinical measure after 6 months (3).
Addressing instability through gait interventions early post-injury appears essential to the long-term prospects of reducing temporal variability. During PP walking, all groups appeared to reduce step length variability to values similar to NT controls. Perhaps, as Brach et al. (218) proposed, using visual cues (i.e., markings on the floor) to improve uniformity in step length may be more feasible to implement than training to achieve consistency in step time (i.e., training with a fixed auditory cue). Thus, reducing step length variability post-injury may be an easier undertaking than reducing step time variability. In addition, a reduced PP variability does not appear to necessitate reduced MP variability. The least severely injured group demonstrated reduced PP variability throughout the assessment period, yet during MP walking conditions had a step time and step length variability that was not different from individuals sustaining the most severe brain injury.

It is important to examine all three facets of gait variability independently, as these measures represent different aspects of gait. Step time variability and step length variability are markers of timing and pattern generation, while balance control is believed to be represented best in the measure of step width variability (106). There were no clear group distinctions or effect of time in terms of step width variability and all groups were similar to the control sample or reference values (111). This finding aligns with those of Niechwiej-Szwedo et al. (63) which concluded that step width variability following TBI was not distinguishable from NT controls under PP or MP walking conditions.

Changes in gait symmetry in the first year following brain injury have been previously described. Walker et al. (3) demonstrated that the number of people with hemiparetic gait patterns dropped from 53% to 12% over the first 2 years post-injury, with the most change occurring in the first 6 months. From a spatiotemporal perspective, Wade et al. (31) demonstrated that in the first few months following TBI, bilateral differences in step length decreased. In line with previous research, a decrease in temporal asymmetry occurred between 2 and 5 months during PP and MP walking. All LPTA groups appeared to demonstrate a plateau in bilateral swing time differences at 5 months, which for the LPTA group that did not demonstrate a sufficient early recovery (i.e., >4 weeks LPTA), resulted in more asymmetric gait pattern long-term compared to other severity groups. Symmetry was a distinguishing feature between injury severity groups as individuals.
with an LPTA >4 weeks had greater PP and MP swing time ratios than groups less severely injured. During MP conditions only, there was also a difference between the most severely injured group and individuals with an LPTA duration of 1-7 days and 1-4 weeks in terms of step length ratio. Although the different measures of gait symmetry illustrated distinguishing features of each severity group, when compared with NT controls, most LPTA groups were in general no more asymmetric than controls. Only PP swing time ratio was higher than NT values for the most-severely injured group at 12 months post-injury, but within the upper 95% confidence limit established for NT controls by Patterson et al. (219). In a longitudinal assessment of gait symmetry post-stroke, Patterson et al. (220) noted that changes in step length symmetry between admission and discharge from inpatient rehabilitation were associated with changes in velocity, while swing time symmetry was linked to weight bearing on the more affected limb in standing. In the current study, as velocity returns to NT values, it coincides with a reduction in PP and MP step length ratios. However, the same pattern does not appear to exist for swing time ratio as the most severely injured LPTA group increased PP swing time ratio between 5 and 12 months to values above that of NT controls. The plateau experienced by the most severely injured group at 5 months post-injury may help therapists gauge when to make strength and coordination exercises that emphasize restoration of temporal symmetry a greater point of emphasis in physical rehabilitation (59).

Following TBI, many individuals adopt a broad step width to accommodate for increased dynamic instability (57). In the current study, step width did not change over the course of the first-year post-injury, echoing findings conducted in children in the acute stage of recovery after TBI (29). Step width was a distinguishing feature between severity groups as during both walking conditions the most severe LPTA group consistently had the highest step width. The two most severely injured LPTA groups had MP step width values that were higher than the sample of NT controls. However, these values were less than previously reported by Inness et al. (65) during MP conditions (15.77 cm (SD=26.8)). At both PP and MP walking conditions, individuals with a LPTA of >4 weeks in Williams et al. (57) study demonstrated a greater stride width than the sample of NT controls. This finding is not universally reported in TBI research as step width values have often been found to be statistically indistinguishable from those of NT individuals (63).
Over the course of the first-year post-injury, the improvement in dual-task walking speed did not match improvements made in single-task walking speed, as evidenced in the increasingly negative dual-task effect over time. The value appears to become more negative over time, suggesting that the difference between single and dual-task walking performance increased. Initially, the least severely injured group appeared to be capable of walking at faster speeds during dual-task performance than single-task walking. This finding could be representative of an unsafe dual-task prioritization strategy commonly characterized in PD patients (156,221). Valuing the retention of walking speed at the expense of stability during dual-task performance has been referred to as a ‘posture-second’ adaptation (221,222). Over time, this severity group appeared to reduce dual-task walking speeds compared to single-task performance. At 12 months post-TBI, all severity groups demonstrated a significantly greater dual-task cost compared with NT controls. In a sample of 30 individuals with ischemic stroke living in the community, an 8.3% reduction in preferred walking speed was noted with an accompanying serial subtraction task (223). This percentage decrease exhibited by individuals post-stroke appears similar to the detriment experienced by those following a TBI. Characterizations of dual-task recovery following TBI have often been studied under the umbrella of ABI (23). Haggard et al. (82) reported on longitudinal changes in stride duration during dual-task performance, which is more difficult to interpret than changes in walking velocity. In the 2000 study, only dual-task effect of the visuospatial dual-task demonstrated improvement, but overall single-task recovery outpaced dual-task recovery (34). Reducing walking speed while dual-tasking could be a byproduct of prioritizing stability or a difficulty with gait automaticity after brain injury. In the present study, we did not assess change in measures of step-to-step variability during dual-task walking, thus it is unclear if the reduction in dual-task walking speed coincided with reduced step-to-step variability. Furthermore, a decrease in dual-task walking speed may have translated to improved cognitive performance, but this information was not accessible for analysis.

Research suggests that stability, symmetry, efficiency, and dual-task performance demonstrate greater sensitivity than forward progression measures to detect high-level mobility impairments after TBI (3,57,64,67,82). Thus, we anticipated that more individuals would continue to present with lingering impairments in these aspects of gait regardless of speed restoration. As evidenced
in our findings, cadence was the only measure of forward progression to deviate from NT values, while walk ratio, step time variability, swing time ratio and dual-task effect produced a more extensive array of impairments at 1-year post-injury.

Following TBI, mobility is a requirement for obtaining independence in many daily activities and is associated with increased community integration (65,86). An individual’s ability to participate in the community post-TBI has been described as the link between injury impairments and quality of life (224,225). Evaluating the association between mobility and levels of community integration following TBI has previously been assessed (65,86), yet to date, velocity is the only spatiotemporal outcome measure that has been correlated with community integration (125). Although clinical measures of balance, high-level mobility, and gait speed have been compared with CIQ scores (65,86,125), few studies have analyzed the longitudinal relationship, both concurrently and predictively, between mobility and community integration (126). In a doctoral dissertation, Frasca et al. (126) correlated single-task and multi-task components of the CB&M at 5 and 12 months post-injury, both concurrently and predictively, with CIQ total and sub-score outcomes at 5, 12, and 24 months post-TBI. In the 2015 dissertation, a relationship between high-level motor ability existed early post-injury but dissipated over time (126). Multi-task components of the CB&M appeared to have a stronger association with community integration even as late as 2 years post-injury (126).

In the present study, spatiotemporal measures of gait at 2 months post-injury were not correlated with CIQ total or subscale scores at any of the later assessment time points. Previous findings have noted an association between initial disability severity and home and social integration, return to work, and independent mobility later in the recovery process (27,93,211). Individuals in the present study that were unable to walk independently (i.e., without a walker) (n=5) or presented with an orthopedic injury (n=5) at 2 months were excluded from this portion of the analysis. As such, the removal of individuals demonstrating greater walking impairment and orthopedic comorbidities at 2 months post-injury may have affected the correlation between early gait measures and community integration. By 5 months post-injury, the group of individuals with incomplete 2 month assessments walked with an average PP velocity of 128 cm/s (SD=30), which reflects a NT walking speed (215,226). Perry et al. (229) demonstrated a
moderate positive correlation between PP walking speed and CIQ productivity sub-scale scores following TBI. The average walking speed of individuals in the 2014 study was 113 cm/s after excluding the 4 fastest walkers who demonstrated preferred walking speeds of 225 cm/s to 530 cm/s (125). Compared to the present study, individuals in Perry et al. (125) had walking speeds similar to the group with an LPTA >4 weeks and lower than the other two severity groups at 5 months. By 12 months, all severity groups had a greater walking speed than 113 cm/s. Although the finding did not remain significant after correcting for multiple comparisons, PP velocity had a moderate positive correlation with CIQ social scores at 5 months after controlling for age, sex, and injury severity (r=.39, p=.0061). While there was a difference in time since injury between participants in Perry et al. (125) and the current study, walking speed appears to be related to community integration when velocity is below the threshold of community ambulation established by Fritz et al. (226) of 120 cm/s. These findings suggest that for individuals with reduced mobility following TBI, walking speed may be a sufficient measure of concurrent community integration. However, for individuals with increased walking speeds, other measures such as walking stability may have a stronger link with community integration.

In a concurrent correlation between gait and community integration at 5 months post-injury, PP step time variability and CIQ total scores demonstrated a moderate negative association. Thus, individuals presenting with more instability after TBI experienced greater difficulty in all aspects of community integration. This finding was not statistically significant until the effects of age, sex, and injury severity were controlled for, further emphasizing the importance of taking these demographic and injury-related variables into consideration when making comparisons between mobility and community integration (125,126). At 5 months, step time variability was also negatively correlated with CIQ home subscale scores (r=-.37, p=.0096). Although this finding did not survive the correction for multiple comparisons, the non-significant result provides clarity as to which aspect of community integration gait instability impacts most. Between 3 to 6 months post-TBI, CIQ home subscale scores have been shown to improve, with complete restoration achieved by the 1 year mark (227). Thus, an unstable walker may be less inclined, confident, or capable of completing everyday housework or household shopping. Considering this, if a high step time variability is noted early post-injury, adaptations should be made to
anticipate difficulties individuals may experience related to home and community integration associated with this gait impairment.

A high step time variability has been linked to impairments in executive function (228). Additionally, Rapport et al. (229) noted that executive function impairments were a significant predictor of falls in TBI rehabilitation. This finding was attributed to a reduced self-awareness, risk-assessment skills, attentional issues, and impulsivity (229). These cognitive impairments combined with an unstable gait may have resulted in unsafe behavior and an increased likelihood of an adverse event in the home and community in the present study.

To compensate for increased gait instability post-injury, some individuals employ a wider step width to magnify the base of support and improve responses to perturbation (230). A wider step width is a cautious and safe adaptation but may not be an ideal long-term solution as the underlying neuromotor impairment causing the instability may remain unaddressed. Maki et al. (110) demonstrated that older adults with a wider step width were more likely to fall and had a greater fear of falling. A wide step width was described as a fear-based compensation in older adults along with reduced step length and velocity (110). Maki et al. (110) also noted that increased step-to-step variability was associated with falling but not with a fear of falling. This conceptual framework could provide an interestingly psychological link between community integration and gait post-injury.

The reason for reduced community integration early post-injury may be associated with increased frequency of falling, yet as individuals become more aware of injury-related limitations over time, community integration may be influenced by psychological fear-based adaptations. Fear of falling has been assessed following brain injury by Collicutt-McGrath (231). TBI patients (n=82) with a median LPTA of 7 weeks (time since injury: 28.3 weeks) were assessed for a fear of falling during physical and occupational therapy using self-rating reports and observer evaluation (231). Sixty-four percent of the study participants reported experiencing fear of falling and observers reported fear of falling in ~35% of participants (234). Considering the work of Collicutt-Mcgrath (234), future studies should assess the association between spatiotemporal gait and gait confidence over the course of recovery post-TBI. In the past, Inness
et al. (65) demonstrated an association between performance on the CB&M and the Activities-specific Balance Confidence (ABC) Scale (232) and Mendley et al. (233) noted that scores on the Dynamic Gait Index were associated with Falls Efficacy Scores (234), a measure an individual’s perception of stability during everyday activities.

Adopting a wider step width causes the centre-of-mass velocity to exhibit more frequent and smaller in amplitude changes in direction (230). The altered harmonic motion can cause increased energy expenditure, thereby increasing the likelihood of gait-related fatigue during community-based excursions (230). In the present study, a wider MP step width at 5 months post-TBI was correlated with CIQ total scores at 24 months post-injury. CIQ home subscale scores at 24 months were also strongly correlated with MP step width ($r=-.55$, $p=.004$). Although the latter finding did not survive multiple comparison corrections, it provides additional detail about the relationship between the instability compensation and reduced community integration. The association between compensating for instability and reduced community integration persisted at 1-year post-injury as MP and PP step width were negatively correlated with CIQ total and CIQ home scores at 24 months post-injury, respectively. In line with our third hypothesis, measures of instability and the compensation associated with instability demonstrated a higher concurrent and predictive relationship with measures of community integration, than measures of forward progression. In a review of TBI recovery, Hylin et al. (5) noted that obtaining independence, rather than the addressing the underlying impairment, is often the overriding focus of rehabilitation. Thus, obtaining independence, defined as a walking speed of 120 cm/s, early post-injury may come at the expense of developing compensations that can negatively dictate long-term outcome (226).

One limitation associated with this study is that all subjects were drawn from a TBI population receiving medical care at a single institution. Additionally, there is no available record of the physiotherapy treatment received by each study participant. Another limitation associated with this present study surrounds a lack of kinematic and kinetic measures related to the change in spatiotemporal gait patterns over time and between groups. This additional information could have provided causality behind the changes, or reluctance to change, in particular spatiotemporal features of the gait cycle (58). However, the reliance on spatiotemporal measurements and
assessment tools may have greater clinical applicability and feasibility than 3DGA (94). Due to the longitudinal nature of this analysis, some individuals were either unable to complete the first assessment due to reliance on a walking aid or an orthopedic injury and others missed the final evaluation. Although the group that missed the final evaluation did not have a notably greater walking speed (124.1 cm/s (SD=9.2)) at 5 months than the rest of the sample, the absence of these individuals could have influenced the relationships between CIQ values and gait measures. Additionally, the rate of CIQ completion was not uniform across time points, which could have affected correlations with spatiotemporal measures.

In conclusion, the findings from this study highlight the necessity for a detailed examination of gait post-TBI. This longitudinal analysis has added to the understanding of patterns of change in spatiotemporal measures of post-TBI gait and the specific nuances that distinguish individuals of different injury severities. With such information, clinicians can design dynamic and informed rehabilitation plans with multifaceted goals based on the time post-injury and an individual's injury severity. In future research, the rehabilitation community should explore gait interventions to meet the unaddressed needs of this population and determine when it is best to employ particular gait training techniques. Finally, if instability or compensations associated with instability are present following brain injury, patients and their circle-of-care can strategize to make appropriate life adaptations to address problematic facets of prospective community integration.
3 Study 2: Feasibility of a rhythmic auditory stimulation gait training intervention in community-dwelling adults after moderate-severe traumatic brain injury

Abstract
This case series explored the feasibility of RAS as a gait-training technique in community-dwelling adults following moderate-severe TBI. Two individuals with a TBI participated in 9 sessions of gait training with RAS over a 3-week training period. Feasibility measures included acceptability, demand, implementation, and preliminary efficacy. Assessments of acceptability included patient reported outcomes measuring physical fatigue before and after each training session and a questionnaire assessing participants’ perceptions of the intervention. Measures of demand included interest and recruitment rates. The number of staff and therapists required to conduct the intervention served as a measure of implementation. An assessment of preliminary efficacy occurred at a baseline, post-training, and 3-week follow-up assessment using measures of spatiotemporal gait (pressure sensitive mat), higher-level mobility (CB&M), and walking endurance (6MWT). Spatiotemporal measures of gait included velocity, cadence, stride/step length, walk ratio, step time variability, step length variability, stride width variability, step width, step length symmetry, and swing time symmetry. Gait data collection occurred while participants walked at both PP and MP. Dual-task walking performance was also assessed before and after the RAS intervention. In this case series, preliminary evidence suggests that RAS is a feasible intervention capable of improving gait impairments related to forward progression, instability, asymmetry, and dual-task performance.
3.1 Introduction

Impairments in gait are common following moderate-severe TBI (48,56,57,59,60,62–64,66,68,69,72,74,75,78,79) and a reduction in walking ability can significantly impact an individual’s ability to integrate with their community, ultimately reducing quality of life (65,85,86,126). After brain injury, spatiotemporal deviations in gait include a reduced walking speed (28–30,42,47,56–59), instability (29,48,58,62–74), asymmetry (28,31,48,56,75–80), and inability to dual-task (64,81–83). These issues can arise as a result of reduced muscle strength (57,73), coordination issues (61,93), or cognitive impairments (81,101,120). Kinetic and kinematic problems often accompany spatiotemporal abnormalities (57,58,93). Individuals with TBI appear to generate less push-off strength than NT individuals, ultimately compensating for reduced ankle joint power generation by increasing hip power generation (57). Gait impairments can remain long after injury (103), and although research into specific gait interventions exists (19), there is little information on the effectiveness of a gait intervention used in stroke and PD, RAS (127,230). RAS relies on the association between audio-motor neural pathways to entrain motor movements to the timing structures inherent to music. An external auditory source (i.e., a metronome) provides auditory information related to timing and rhythm. The rhythmic pattern can be used to shape and optimize neuromotor control (147). Motor regions of the brain can synchronize to the rhythm and timing of auditory neural patterns induced by an external cueing source. Thus, repetitive movements such as walking can become more coordinated and optimized in both time and space (147). Many of the lower limb muscles that have been described as lacking temporal coordination post-TBI (61) overlap with the muscles RAS has been shown to offer improved temporal coordination (236,237).

Presently, only a few studies have explored the effectiveness of RAS in gait post-TBI (76,135,143). Hurt and co-authors (77) in 1998 were the first to assess the application of RAS in TBI. In a two-part analysis, 8 participants (age: 30 years (SD=5)) were assessed to determine the immediate effect of RAS on gait (76). These participants had previously completed conventional therapy and still possessed lingering deficits concerning speed, cadence, stride length, and symmetry, yet could ambulate independently or with physical assistance (76). First, individuals walked at PP and MP conditions uncued, and a participant’s cadence was then used to set the metronome pulse sequence embedded in the rhythmically accented music (76). When walking
uncued, all individuals at baseline presented with values of speed, cadence, stride length, and symmetry (shorter swing time divided by longer swing time) that were below normative values. However, when introduced to RAS, all parameters increased during PP walking (76). Under MP conditions, velocity decreased during cued walking compared to uncued walking, due to a reduction in step length, while cadence, and swing symmetry ratio improved towards normal values (76). The authors noted that this finding was a result of 2 participants with the lowest baseline walking speed who could walk faster without rhythmic cueing, but reduced velocity when walking with a cue in the fast-paced condition (76). Other than these individuals, 88% of participants increased their walking speed during PP conditions, and 75% did so during MP conditions (76). Although the changes in velocity were nonsignificant, after excluding the 2 individuals with slow walking speeds, all individuals with TBI demonstrated an immediate response to the rhythmic cueing and were able to improve measures of forward progression.

In the second phase of this study, 5 individuals of the previous 8 completed a five-week, at-home RAS training intervention and changes in uncued walking were assessed (76). After each week of training, a reassessment of walking endurance occurred, and the duration of time allotted to walking at PP and MP with RAS increased by 1 minute each week (76). After the training period, individuals significantly increased walking speed, cadence, and stride length during PP walking and made a nonsignificant increase in swing time ratio (76). During MP conditions, gains were made in all 4 outcome measures although these findings did not reach significance (76). One of the most enticing findings of this study was the increase in a spatial outcome (i.e., stride length) with the use of a temporal gait training technique (i.e., auditory stimulus). This finding suggests that individuals are not just using the beat to match their steps with, but the time between beats was also used as a scaffold to structure and shape motor movement in space (238). These findings were further supported by a dissertation by Wilfong et al. (143) demonstrating that a 3-week RAS intervention improved the average velocity, stride length, and cadence of a group of 7 individuals following TBI; however, no assessment of a long-term retention or carry-over effect took place in this study.

These preliminary findings, along with work done more recently using RAS in children and adolescents with ABI (135), shows the promise of RAS as a TBI gait intervention. In this case
series, we explore the feasibility of RAS as a TBI gait-training technique, in preparation for a RCT comparing RAS with conventional gait training in adults. Many RCTs assessing RAS efficacy exist in other neurological populations such as stroke and PD, and many of the gait impairments present in these conditions overlap with those of TBI (144,235). Furthermore, recent findings suggest that RAS training can improve dual-task function and gait variability (113), two areas of concern for individuals with a TBI. To date, research exploring the benefits of RAS on step-to-step variability, walk ratio, spatial symmetry, and dual-task walking in TBI does not exist. Information gathered in this case series will aid in the design and implementation of an RCT comparing RAS and conventional gait training in community dwelling adults with TBI.

3.2 Methods

3.2.1 Participants

This case series included participants with a TBI who completed conventional rehabilitation and were living in the community with ongoing gait impairments. Participants were screened based on self-report in accordance with the following criteria: (1) acute care diagnosis of TBI, (2) able to walk at least 10 meters unassisted, (3) self-reported ongoing gait abnormalities resulting from a TBI, (4) no concurrent co-morbid neurological or orthopedic conditions that impede walking ability (i.e., PD or fractured hip not resulting from TBI), and (5) no severe hearing loss. Research staff screened participants for hearing impairments using an audiometer and for capacity to consent determined by a Montreal Cognitive Assessment Score (MoCA) threshold of ≥22 (239). Researchers obtained written informed consent from each participant. Research staff collected information regarding current age, and cause and date of brain injury at the baseline assessment (Table 3.2). Administration of the MoCA occurred before the baseline gait assessment to characterize the severity of impairment in cognition (240). The MoCA assesses 8 neurocognitive domains: visuospatial/executive functioning, naming, memory, attention, language, abstraction, delayed recall, and orientation (240).

3.2.2 Procedures

The Health Sciences Research Ethics Board reviewed and approved all procedures. Following baseline testing, participants completed 9 sessions of RAS gait training, 30 minutes each session,
3 times per week for 3 weeks. Completion of a post-training assessment occurred within 1 week of the last training session. Training was provided by licensed neurological music therapists (NMT) and a trained researcher conducted all of the outcome assessments.

### 3.2.3 Intervention

RAS was provided live by a NMT following the principles outlined in The Handbook of Neurologic Music Therapy 6-step RAS intervention (241). Thirty-minute sessions were broken down into 10 minutes of pre-gait exercises (i.e., rocking heel-to-toe or marching), 10 minutes of task-specific training (i.e., walking), 5 minutes of advanced gait exercises tailored to the participants functional level and needs (e.g., different surface walking, stairs, stepping over objects), and 5 minutes of activities open to therapist's discretion and aligned participant's functional level and goals. Therapists were advised to spend at least 70-80% of the time walking. Music recordings set to predetermined frequencies were provided with the presence of metronome beats.

### 3.2.4 Outcome measures

In accordance with guidelines provided by Bowen et al. (242), measures of feasibility included acceptability, demand, implementation, and limited efficacy. A questionnaire administered at the end of the final training session provided an indication of the participants’ general satisfaction with the intervention. Adherence and acceptability were determined using data records from training personnel and fatigue monitoring performed before and after each training session with the administration of the Borg Rating of Perceived Exertion (RPE) Scale. The 15-point scale (6=no exertion at all to 20=maximal exertion) provides scores that increase linearly with the intensity of exercise (243) and has demonstrated validity and reliability during exercise to capture the perceived degree of exertion (244). The specific intensity categories associated with the RPE have been previously determined by the American College of Sports Medicine (245). The measure of implementation included a record of staff and therapists required to administer training sessions and conduct assessments.

Measures of preliminary efficacy include spatiotemporal measures of gait collected at PP and MP walking conditions. Performance of all gait assessments occurred without a cue as this study
was interested in the carry over effects of training from cued to uncued walking. Gait parameters were measured using a pressure-sensitive mat (Protokinetics, Havertown, PA, USA), with a 2-meter runoff at each end to allow for deceleration and turning. During each condition, participants walked back and forth across the mat until 18 footfall events had been collected to ensure the reliability of the measurement. The spatiotemporal measures reported in this study include: velocity (cm/s), cadence (steps/min), stride length (cm), step length (cm), walk ratio (cm/(steps/minute)), stride width (cm), step time variability (%CV), step length variability (%CV), stride width variability (%CV), step length ratio, and swing time ratio (see Table 3.1 for definitions). All measures of variability were reported as a coefficient of variation (%CV), the formula for determining this value can be found in Equation 3.2.

In addition to PP and MP walking, an assessment of dual-task performance occurred. The dual-task selected for this study was a serial subtraction cognitive task. In prior research assessing the effect of a RAS intervention on dual-task performance in PD, the authors selected a serial subtraction task to assess the motor-cognitive dual-task performance (246). In this case series, participants subtracted from a random three-digit number provided before beginning walking and were instructed to give equal priority to both tasks. The motor dual-task effect represents the relative change in performance in the dual-task condition compared to single-task performance. Dual-task effect of walking speed, for instance, was calculated by subtracting dual-task walking speed by single-task walking speed and dividing by single-task walking speed multiplied by 100 (see Equation 3.1)(247). Walking speed is the most sensitive spatiotemporal measure of change during dual-task walking (117). Additionally, motor dual-task effects are the most commonly displayed cost for individuals with TBI, thus cognitive dual-task effects were not calculated for this feasibility study and only raw cognitive dual-task scores will be discussed, although it limits the present findings (120). Step time variability is a marker of gait stability and a reduction in step time variability allows for an increasingly autonomous gait pattern (248). It has been previously reported that patients with dementia and impaired executive functions demonstrate changes in step time variability while counting backward, making step time variability another informative marker of dual-task performance (248).
All spatiotemporal measures were compared to age-matched NT values previously reported in the literature for velocity, cadence, stride length, and step length (215), and measures of variability, symmetry, and dual-task effect were compared to data collected from a sample of 29 NT individuals (40.4 years (SD=17.2), males: 14, female: 15) using similar gait analysis and collection techniques.

Administration of the CB&M occurred at all 3 assessments and is a commonly used measure of high-level mobility in TBI research. The measurement tool is composed of 13 challenging tasks assessing balance and gait, some performed unilaterally and others bilaterally (188). The CB&M has demonstrated validity, reliability, and internal consistency and has a minimal detectable change of 9.6 (Cronbach’s alpha value) and 7.5 (test-retest ICC values) (188). The 6MWT is valid and reliable measurement of walking endurance for individuals with TBI. Between admission and discharge from a post-acute rehabilitation facility after TBI, 6MWT values have been shown to increase from 342.6 to 408.9 meters (249). The minimal detectable change in the 6MWT has been previously determined to be ≥36 meters post-stroke and ≥45 meters post-TBI (250,251).

**Equation 3.1**

\[ DTE\% = \frac{DT\ value - ST\ value}{ST\ value} \times 100 \]

**Equation 3.2**

\[ \%CV = \frac{Standard\ Deviation}{Mean} \times 100 \]
Table 3.1 – The definition of spatiotemporal parameters and their units of measurement.

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<thead>
<tr>
<th>Spatiotemporal Parameter</th>
<th>Units</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (mean)</td>
<td>cm/s</td>
<td>Calculated by dividing the sum of all stride length measurements by the sum of all stride time measurements of both feet (cm/sec).</td>
</tr>
<tr>
<td>Cadence (mean)</td>
<td>steps/min</td>
<td>The number of footfalls minus one divided by the ambulation time converted to minutes (steps/min).</td>
</tr>
<tr>
<td>Stride Length (mean)</td>
<td>cm</td>
<td>The distance from the heel of one foot to the following heel of the same foot.</td>
</tr>
<tr>
<td>Step Length (mean, %CV, ratio)</td>
<td>cm, %, ratio</td>
<td>Step length is the distance between corresponding successive heel points of opposite feet, measured parallel to the direction of progression for the ipsilateral stride.</td>
</tr>
<tr>
<td>Stride width (mean, %CV)</td>
<td>cm, %</td>
<td>Stride width is the perpendicular distance between the line connecting the two ipsilateral foot heel contacts (stride) with the contralateral heel contact between those events.</td>
</tr>
<tr>
<td>Step time (%CV)</td>
<td>%CV</td>
<td>The period of time taken from one step measured from the first contact of one foot to the first contact of following other foot, measured for the stride of which it is the second part.</td>
</tr>
<tr>
<td>Swing Time Ratio</td>
<td>ratio</td>
<td>Swing time is the period of time the foot is not in contact with the ground in seconds.</td>
</tr>
<tr>
<td>Walk Ratio</td>
<td>cm/(steps/min)</td>
<td>Mean values of step length for an individual walking trial divided by the cadence.</td>
</tr>
</tbody>
</table>
### 3.3 Results

Both participants completed 9 sessions of gait training with RAS. Completion of all training sessions occurred within the 3-week time-frame (±3 days). The average time between baseline and post-intervention assessments was 30 days and from post-intervention to follow-up was 23 days. The baseline characteristics and demographics of the participants can be found in Table 3.2.

**Table 3.2 - Demographic information of participants.**

<table>
<thead>
<tr>
<th>ID</th>
<th>Age</th>
<th>Sex</th>
<th>Etiology</th>
<th>TSI(years)</th>
<th>MoCA</th>
<th>CB&amp;M</th>
<th>6MWT</th>
<th>Velocity(cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>42</td>
<td>M</td>
<td>MVA (pedestrian)</td>
<td>26</td>
<td>22</td>
<td>31</td>
<td>310</td>
<td>74.7</td>
</tr>
<tr>
<td>P2</td>
<td>54</td>
<td>M</td>
<td>MVA (driver)</td>
<td>18</td>
<td>25</td>
<td>24</td>
<td>285</td>
<td>125.2</td>
</tr>
</tbody>
</table>

P1 = Participant 1, P2 = Participant 2, TSI = Time since injury, MoCA=Montreal Cognitive Assessment Tool (≥ 26 NT), MVA= Motor Vehicle Accident, CB&M=Community Balance and Mobility Scale, 6MWT=6-Minute Walk Test.

#### 3.3.1 Acceptability, demand, and implementation

Twenty-eight individuals were interested in participating in the study after reading the recruitment poster. Twenty-three individuals remained interested after hearing more about the study via phone call. Of the 5 individuals who were no longer interested in participating, 3 participants cited the study’s time commitment and noted that their current place of residence limited potential prospective participation. One participant was no longer interested after the terms of financial compensation were clarified and another did not respond to the follow-up phone call. Of the 23 individuals interested in participating in the study, only 7 were deemed eligible. Eight individuals were excluded as they reported neurological conditions other than a TBI. Three individuals had a TBI, however, also had a concurrent neurological or orthopedic condition that resulted in exclusion. Five individuals called interested in participating, yet did not report difficulty walking. In all, five subjects were recruited to the study, but 2 dropped out, and one received conventional gait training as a component of a larger RCT. The first individual dropped out because of an inability to complete the assessment protocol due to the physical and cognitive burden, while the second participant was unable to complete the intervention due to the time commitment and long commute to the training facility. Training sessions required 1-2 NMT to be present, and assessments required 2 research staff to be present for data collection and safety. Both participants reported improvements in gait, balance, strength, endurance, coordination, and mood. The participants also noted that their time was well spent participating
in the intervention and would recommend the intervention to a friend. Finally, the participants reported they would continue participating in the gait intervention if possible. Participant 1 (P1) reported RPE scores representative of light exertion after the first 4 RAS sessions; however, by the fifth RAS session, P1 noted the training to be very light (average RPE: 9.6) (245). Participant 2 (P2) reported RPE values ranging from light to very high (11-17) (average RPE: 13.8) (245).

3.3.2 Preliminary efficacy
A summary of change after the RAS intervention is provided below for each participant followed by a discussion of common responses between participants. Performance of all gait assessments occurred without a cue as this study was interested in the carry over effects of training with RAS to uncued walking.

Participant 1 (P1): P1 exhibited an improvement in PP and MP velocity, step length, cadence, and walk ratio after RAS (with the exception of MP cadence) (Figure 3.1-3.4) (see Table 3.3 for all spatiotemporal values for P1). All of these measures of forward progression sustained improvement at a 3-week follow-up assessment. P1 minimized the difference between PP and MP walking speeds after the RAS intervention, indicating that the improvement in PP speed was greater than MP speed (Table 3.5). To increase walking speeds at baseline, P1 relied on a more considerable increase in cadence compared to step length, an atypical pattern which persisted after the RAS intervention (Table 3.5). Markers of gait stability and timing, such as step time variability, step length variability, and step width variability that were above or below NT values at baseline, returned to within the NT range immediately following the RAS intervention or by a 3-week follow-up assessment (Figure 3.5-3.7). Step width was within NT range during PP walking and remained so throughout the RAS training period. MP step width remained above NT values over the course of the assessment period, suggesting instability at MP walking conditions did not improve (Figure 3.8). Compared to baseline values, P1 demonstrated a reduced step length ratio after the RAS intervention. These values were reduced to within the range of the NT sample at both post-training and follow-up assessments (although values at all assessments were within NT confidence limits established by Patterson et al. (219)) (Figure 3.9). Temporal symmetry at baseline exceeded NT values in the present study and in Patterson et al. (219) for PP walking. After training, these values returned to within the NT range, but unlike the
improvements in spatial symmetry, improvements in temporal symmetry were not as effectively retained at a 3-week follow-up assessment, as values appeared closer to the threshold of asymmetry (219)(Figure 3.10). Swing time ratio at MP walking conditions became more asymmetric over the course of the assessment period compared to baseline values. Dual-task walking became more stable (according to the dual-task effect on step time variability) and faster (according to the dual-task effect on velocity) over the course of the assessment period (Table 3.3). Walking endurance and high-level mobility improved according to changes in the 6MWT and CB&M (Table 3.6).

### Table 3.3 – Change in Spatiotemporal Measures for Participant 1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Pre</th>
<th>%NT</th>
<th>Post</th>
<th>%NT</th>
<th>% Δ</th>
<th>3-wks</th>
<th>% NT</th>
<th>% Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (cm/sec)</td>
<td>PP</td>
<td>74.7</td>
<td>56.2</td>
<td>105.9</td>
<td>79.8</td>
<td>+41.9</td>
<td>109.2</td>
<td>82.2</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>95.9</td>
<td>55.9</td>
<td>118.5</td>
<td>68.9</td>
<td>+23.4</td>
<td>119.2</td>
<td>69.4</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>PP</td>
<td>103.9</td>
<td>86.2</td>
<td>108.2</td>
<td>89.8</td>
<td>+4.2</td>
<td>109.3</td>
<td>90.7</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>124.8</td>
<td>87.1</td>
<td>119.5</td>
<td>83.3</td>
<td>-4.3</td>
<td>113.9</td>
<td>79.4</td>
</tr>
<tr>
<td>Stride Length (cm)</td>
<td>PP</td>
<td>86.1</td>
<td>66.5</td>
<td>117.3</td>
<td>90.6</td>
<td>+36.3</td>
<td>119.7</td>
<td>90.1</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>92.3</td>
<td>62.6</td>
<td>118.8</td>
<td>80.6</td>
<td>+28.7</td>
<td>125.6</td>
<td>85.2</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>PP</td>
<td>43.2</td>
<td>66.7</td>
<td>58.7</td>
<td>90.7</td>
<td>+36.1</td>
<td>59.6</td>
<td>92.2</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>46.2</td>
<td>62.7</td>
<td>59.4</td>
<td>80.6</td>
<td>+28.6</td>
<td>62.6</td>
<td>84.9</td>
</tr>
<tr>
<td>Stride Width (cm)</td>
<td>PP</td>
<td>9.3</td>
<td>106.2</td>
<td>9.1</td>
<td>103.7</td>
<td>-2.4</td>
<td>9.1</td>
<td>103.8</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>10.3</td>
<td>126.3</td>
<td>10.8</td>
<td>131.7</td>
<td>+4.3</td>
<td>10.3</td>
<td>126.6</td>
</tr>
<tr>
<td>Walk Ratio (steps/min)</td>
<td>PP</td>
<td>0.42</td>
<td>63.9</td>
<td>0.54</td>
<td>83.4</td>
<td>+30.6</td>
<td>0.55</td>
<td>83.9</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>0.37</td>
<td>57.0</td>
<td>0.50</td>
<td>76.5</td>
<td>+34.4</td>
<td>0.55</td>
<td>84.6</td>
</tr>
<tr>
<td>STV (%CV)</td>
<td>PP</td>
<td>6.2</td>
<td>199.6</td>
<td>3.6</td>
<td>199.6</td>
<td>-42.5</td>
<td>3.4</td>
<td>110.6</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>6.6</td>
<td>163.5</td>
<td>5.2</td>
<td>129.5</td>
<td>-20.8</td>
<td>3.7</td>
<td>92.6</td>
</tr>
<tr>
<td>SLV (%CV)</td>
<td>PP</td>
<td>10.5</td>
<td>285.0</td>
<td>3.7</td>
<td>100.2</td>
<td>-64.8</td>
<td>3.5</td>
<td>94.6</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>9.0</td>
<td>250.5</td>
<td>4.2</td>
<td>117.6</td>
<td>-53.0</td>
<td>3.6</td>
<td>99.3</td>
</tr>
<tr>
<td>SWV (%CV)</td>
<td>PP</td>
<td>18.0</td>
<td>72.4</td>
<td>18.8</td>
<td>75.8</td>
<td>+4.7</td>
<td>20.7</td>
<td>83.3</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>14.0</td>
<td>32.3</td>
<td>20.0</td>
<td>46.2</td>
<td>+42.9</td>
<td>26.4</td>
<td>61.0</td>
</tr>
<tr>
<td>SLR</td>
<td>PP</td>
<td>1.050</td>
<td>102.3</td>
<td>1.028</td>
<td>100.1</td>
<td>-2.1</td>
<td>1.028</td>
<td>100.1</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>1.018</td>
<td>99.7</td>
<td>1.021</td>
<td>100.0</td>
<td>+0.3</td>
<td>1.003</td>
<td>98.3</td>
</tr>
<tr>
<td>STR</td>
<td>PP</td>
<td>1.080</td>
<td>106.3</td>
<td>1.014</td>
<td>99.8</td>
<td>-6.1</td>
<td>1.051</td>
<td>103.4</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>1.021</td>
<td>100.2</td>
<td>1.055</td>
<td>103.5</td>
<td>+3.3</td>
<td>1.069</td>
<td>104.9</td>
</tr>
<tr>
<td>DTE Velocity (%)</td>
<td>NT values: -1.25%</td>
<td>-2.0</td>
<td>-</td>
<td>5.9</td>
<td>-</td>
<td>-</td>
<td>14.9</td>
<td>-</td>
</tr>
<tr>
<td>DTE STV (%)</td>
<td>NT values 19.7%</td>
<td>57.4</td>
<td>-</td>
<td>90.3</td>
<td>-</td>
<td>-</td>
<td>4.1</td>
<td>-</td>
</tr>
</tbody>
</table>

**Participant 2 (P2):** At the baseline assessment, PP and MP velocities were within the range of NT values (Figure 3.1) (see Table 3.4 for all spatiotemporal values for P2). After the intervention, speed was reduced during both walking conditions to values lower than NT individuals. Initially, during PP walking, cadence was higher, and step length was smaller than NT values, yet after the RAS intervention, PP cadence returned to within the NT range (Figure 3.3), and step length further deviated from NT values (Figure 3.2). Baseline MP cadence remained within NT values but decreased over the assessment period. MP step length was within NT values at the baseline assessment but steadily declined after the RAS intervention. This pattern of change of step length (larger decrease) and frequency (smaller decrease) caused the walk ratio to deviate further from NT values after the RAS intervention (Figure 3.4). P2 demonstrated changes in walking velocity between PP and MP conditions that were of similar proportions to previous studies conducted in TBI samples (Table 3.5) (57). Due to the high values of cadence during PP walking throughout all assessments, P2 relied on a more substantial increase in step length than cadence to increase walking speed – a pattern that did not appear to change after the RAS intervention. Measures of PP step time variability, step width variability, and step length variability, increased after RAS, deviating further from the NT values, while MP step time variability, step length variability, and step width variability decreased between baseline to follow-up assessment, thus better approximating NT values (Figures 3.5-3.7). PP and MP step width remained less than NT values over the course of the assessment period (Figure 3.8). At the baseline assessment, spatial symmetry ratios initially exceeded NT values for PP and MP walking (nearing the threshold of asymmetry established by Patterson et al. (219)) and were reduced to within NT values at the post-training assessment. However, this measure exceeded NT values by the 3-week follow-up. At baseline, temporal symmetry at PP and MP conditions were within NT values, yet over the course of the intervention, these values increased and eventually exceeded the range of NT values (Figure 3.10). An increase in dual-task speed and stability was noted when compared to single-task walking, across all assessments (Table 3.4). An increase in cognitive accuracy of dual-task performance was observed at the post-training assessment and improvements were retained at the 3-week follow-up. An improvement in the CB&M and walking endurance was also noted after the RAS intervention (Table 3.6).
### Table 3.4 – Change in Spatiotemporal Measures for Participant 2.

<table>
<thead>
<tr>
<th>P2</th>
<th>Condition</th>
<th>Pre</th>
<th>%NT</th>
<th>Post</th>
<th>% NT</th>
<th>% Δ</th>
<th>3-wks</th>
<th>% NT</th>
<th>% Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (cm/sec)</td>
<td>PP</td>
<td>125.2</td>
<td>100.0</td>
<td>90.4</td>
<td>72.2</td>
<td>-27.8</td>
<td>80.5</td>
<td>64.3</td>
<td>-35.7</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>182.4</td>
<td>111.2</td>
<td>150.2</td>
<td>91.6</td>
<td>-17.6</td>
<td>127.2</td>
<td>77.6</td>
<td>-30.3</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>PP</td>
<td>131.6</td>
<td>111.9</td>
<td>121.1</td>
<td>103.0</td>
<td>-8.0</td>
<td>122.3</td>
<td>104.0</td>
<td>-7.0</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>144.0</td>
<td>122.4</td>
<td>136.4</td>
<td>116.0</td>
<td>-5.3</td>
<td>131.9</td>
<td>112.2</td>
<td>-8.4</td>
</tr>
<tr>
<td>Stride L (cm)</td>
<td>PP</td>
<td>114.2</td>
<td>89.9</td>
<td>89.7</td>
<td>70.6</td>
<td>-21.4</td>
<td>79.3</td>
<td>62.4</td>
<td>-30.5</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>150.5</td>
<td>104.2</td>
<td>131.8</td>
<td>91.3</td>
<td>-12.4</td>
<td>116.1</td>
<td>80.4</td>
<td>-22.9</td>
</tr>
<tr>
<td>Step L (cm)</td>
<td>PP</td>
<td>57.6</td>
<td>90.7</td>
<td>45.1</td>
<td>71.0</td>
<td>-21.8</td>
<td>39.8</td>
<td>62.7</td>
<td>-30.9</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>75.4</td>
<td>104.4</td>
<td>66.4</td>
<td>92.0</td>
<td>-11.9</td>
<td>58.5</td>
<td>81.0</td>
<td>-22.4</td>
</tr>
<tr>
<td>SW (cm)</td>
<td>PP</td>
<td>5.4</td>
<td>61.0</td>
<td>4.2</td>
<td>47.9</td>
<td>-21.5</td>
<td>5.7</td>
<td>65.1</td>
<td>+6.7</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>3.3</td>
<td>40.4</td>
<td>3.6</td>
<td>44.6</td>
<td>+10.3</td>
<td>4.3</td>
<td>53.1</td>
<td>+31.4</td>
</tr>
<tr>
<td>Walk Ratio cm step/min</td>
<td>PP</td>
<td>0.44</td>
<td>67.4</td>
<td>0.37</td>
<td>57.3</td>
<td>-15.0</td>
<td>0.33</td>
<td>50.0</td>
<td>-25.7</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>0.52</td>
<td>80.5</td>
<td>0.49</td>
<td>74.9</td>
<td>-6.9</td>
<td>0.44</td>
<td>68.2</td>
<td>-15.3</td>
</tr>
<tr>
<td>STV (%CV)</td>
<td>PP</td>
<td>7.9</td>
<td>254.1</td>
<td>10.4</td>
<td>334.8</td>
<td>+31.8</td>
<td>9.1</td>
<td>293.5</td>
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<td>MP</td>
<td>5.8</td>
<td>144.8</td>
<td>5.5</td>
<td>137.4</td>
<td>-5.1</td>
<td>5.1</td>
<td>125.8</td>
<td>-13.1</td>
</tr>
<tr>
<td>SLV (%CV)</td>
<td>PP</td>
<td>10.7</td>
<td>290.6</td>
<td>14.5</td>
<td>394.1</td>
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<td>+35.4</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>6.6</td>
<td>184.0</td>
<td>4.8</td>
<td>134.1</td>
<td>-27.1</td>
<td>5.7</td>
<td>159.7</td>
<td>-13.2</td>
</tr>
<tr>
<td>SWV (%CV)</td>
<td>PP</td>
<td>53.7</td>
<td>216.3</td>
<td>76.4</td>
<td>307.7</td>
<td>+42.3</td>
<td>41.4</td>
<td>166.9</td>
<td>-22.8</td>
</tr>
<tr>
<td></td>
<td>MP</td>
<td>119.6</td>
<td>276.5</td>
<td>76.7</td>
<td>177.3</td>
<td>-35.9</td>
<td>61.1</td>
<td>141.3</td>
<td>-48.9</td>
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<tr>
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<td>PP</td>
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<td>104.8</td>
<td>1.050</td>
<td>102.3</td>
<td>-2.4</td>
<td>1.087</td>
<td>105.9</td>
<td>+1.0</td>
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<tr>
<td></td>
<td>MP</td>
<td>1.103</td>
<td>108.0</td>
<td>1.028</td>
<td>100.7</td>
<td>-6.8</td>
<td>1.064</td>
<td>104.2</td>
<td>-3.5</td>
</tr>
<tr>
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<td>PP</td>
<td>1.000</td>
<td>98.4</td>
<td>1.026</td>
<td>101.0</td>
<td>+2.6</td>
<td>1.088</td>
<td>107.1</td>
<td>+8.8</td>
</tr>
<tr>
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<td>MP</td>
<td>1.031</td>
<td>101.2</td>
<td>1.045</td>
<td>102.5</td>
<td>+1.4</td>
<td>1.078</td>
<td>105.8</td>
<td>+4.5</td>
</tr>
<tr>
<td>DTE Velocity (%)</td>
<td>NT values: 1.25%</td>
<td>11.6</td>
<td>-</td>
<td>2.7</td>
<td>-</td>
<td>-</td>
<td>23.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DTE STV (%)</td>
<td>NT values 19.7%</td>
<td>-26.5</td>
<td>-</td>
<td>-30.7</td>
<td>-</td>
<td>-</td>
<td>-27.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


In summary, both participants experienced a change in walking speed following RAS training. The first participant demonstrated an increased walking speed, while the second participant demonstrated a decreased walking speed. Both of these changes were due primarily to modifications in step length rather than cadence. A corresponding increase for P1 and decrease for P2 in walk ratio occurred over the assessment time frame. Both participants demonstrated an improvement in gait variability towards NT values during MP walking conditions; however, only P1 showed improvement in gait variability during PP walking conditions. Stride width values...
remained relatively unchanged for both participants over the assessment period. Both participants experienced reductions in spatial symmetry during PP and MP conditions throughout the assessment period; however, at the 3-month follow-up, P2 did not appear to retain these improvements as well as P1. If temporal symmetry improved over the course of the intervention (i.e., P1 during PP walking), the values at the 3-week follow-up suggest that the findings may not have been retained. Both participants demonstrated improvement during dual-task walking performance over the course of the intervention. For P1, an increase in speed and stability of dual-task walking occurred after RAS, while for P2 the change was best noted in the cognitive component of the dual-task performance.

**Table 3.5** – Percentage change from PP to MP in spatiotemporal measures at all assessments

<table>
<thead>
<tr>
<th>Variable (NT%)</th>
<th>Pre %</th>
<th>Post%</th>
<th>3-wk%</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 Velocity (37.2%)</td>
<td>28.6</td>
<td>11.8</td>
<td>9.2</td>
</tr>
<tr>
<td>Cadence (20%)</td>
<td>20.1</td>
<td>10.4</td>
<td>4.1</td>
</tr>
<tr>
<td>Step L (20%)</td>
<td>7.1</td>
<td>1.2</td>
<td>5</td>
</tr>
<tr>
<td>P2 Velocity (37.2%)</td>
<td>45.6</td>
<td>66.3</td>
<td>58</td>
</tr>
<tr>
<td>Cadence (20%)</td>
<td>9.4</td>
<td>12.6</td>
<td>7.9</td>
</tr>
<tr>
<td>Step L (20%)</td>
<td>30.8</td>
<td>47.4</td>
<td>46.9</td>
</tr>
</tbody>
</table>

**Table 3.6** – Change in secondary outcome measures including CB&M and 6MWT

<table>
<thead>
<tr>
<th>CB&amp;M (/96)</th>
<th>6MWT (distance (m), pre-RPE, post-RPE, 5-min post RPE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
</tr>
<tr>
<td>P1</td>
<td>31</td>
</tr>
<tr>
<td>P2</td>
<td>24</td>
</tr>
</tbody>
</table>

CB&M = Community Balance and Mobility Scale (/96). 6MWT = Six-minute walk test. Columns (left to right) The distance walked in 6 minutes, and the Borg Rating of Perceived Exertion collected before, after and 5 minutes post-completion of the endurance test. (* 60-second rest occurred from 3:10 to 4:10).
Figure 3.1 – Change in PP (left) and MP (right) velocity
Lines represent NT data from men aged 40-59 (215).

Figure 3.2 – Change in PP (left) and MP (right) step length
Lines represent NT data from men aged 40-59 (215).
Figure 3.3 – Change in PP (left) and MP (right) cadence
Lines represent NT data from men aged 40-59 (215).

Figure 3.4 – Change in PP (left) and MP (right) walk ratio
Lines represent NT data from (107).
Figure 3.5 – Change in PP (left) and MP (right) step length variability
Lines represent NT data from the sample population.

Figure 3.6 – Change in PP (left) and MP (right) step time variability
Lines represent NT data from the sample population.
Figure 3.7 – Change in PP (left) and MP (right) stride width variability
Lines represent NT data from the sample population.

Figure 3.8 – Change in PP (left) and MP (right) stride width
Lines represent 95% CI from NT study sample.
**Figure 3.9** – Change in PP (left) and MP (right) step length ratio
Lines represent 95% CI from NT study sample.

**Figure 3.10** – Change in PP (left) and MP (right) swing time ratio
Lines represent 95% CI from NT sample.
3.4 Discussion

We examined the feasibility of RAS as a gait intervention in community-dwelling adults with TBI. The findings from this report provide evidence that a RAS gait intervention is feasible in accordance with measures of adherence including acceptability, demand, implementation, and preliminary efficacy (242).

In the present study, we assessed forward progression, dynamic instability, symmetry, and dual-task gait from a spatiotemporal perspective. Spatiotemporal measures have been commonly used in RAS gait training in ABI research, yet in the past have only assessed velocity, cadence, stride length, step width, and swing time ratio (76,135,143). The addition of step-to-step variability, step length ratio, walk ratio, and dual-task measures to this study ensured that a comprehensive assessment of RAS as a gait intervention occurred. These added measures ensure that this TBI and RAS study aligns with advancements in RAS research recently conducted in older adults, stroke patients, and individuals with PD. Other measures to consider in the future are kinematic and kinetic features of gait. Kim et al. (135) noted in a comparison between adolescents with ABI who received 3-weeks of RAS or conventional gait training, there were differences of hip and knee range of motion in favor of the RAS intervention. In the future, characterizing kinematic/kinetics changes after RAS can provide a mechanistic explanation for the resulting changes in spatiotemporal parameters.

The delivery of the present RAS intervention aligns closely with interventions used by Kim et al. (135). The presence of a therapist for each training session, a clinic-based setting, and the frequency of training (4 weeks x 30 minutes x 3/week: Total = 360 minutes) were similar between both studies (135). By comparison, individuals in Hurt et al. (76) walked daily with RAS for 5 weeks increasing the duration of walking by 1 minute each week, starting at 6 minutes (total = 221 minutes). Apart from reassessments at one week intervals to evaluate walking endurance, there was no therapist guidance in this home-based intervention (76). Our study was the only RAS intervention in TBI individuals to incorporate high-level mobility tasks during training, such as walking on uneven surfaces, stair climbing, and obstacle avoidance (~5 minutes per gait training session).
Due to the variable nature of TBI neuropathology, the associated gait-related impairments are diverse (59). Additionally, this variability in impairment presentation can lead to different responses to specific gait interventions (59). Hurt et al. (76) demonstrated that mean swing time symmetry values improved in a group of 5 individuals after RAS, but the variability between individuals limited the ability to detect significant findings. Furthermore, between-individual variability in response to RAS training was also reported in Wilfong et al. (143). In the present study, the 2 participants demonstrated different responses to the RAS intervention. P1 displayed a more signature pattern of change following RAS previously documented in the literature. A familiar increase in walking speed, cadence, and stride length was observed (19–21). As this participant trained with RAS frequencies above their baseline cadence, improvements in measures of forward progression ensued. In contrast, P2 had a NT walking speed at baseline brought about by an excessively high cadence and reduced step length. For a limited community ambulator reliant on a scooter, this speed was unsustainable and unsafe (226). Over the course of the intervention, P2 demonstrated a slight reduction in cadence to within the NT values during PP walking. The primary contributor to the reduction in speed was a reduction in step length. RAS can reduce elevated step frequencies in individuals with PD (144). Significant reductions in cadence were only demonstrated in these studies after RAS training regimes that occurred more than 5 times per week and lasted more than 30 minutes in duration (144). Although P2 displayed a small reduction in step frequency, with more intensive RAS training, a greater reduction in cadence may have been observed. A greater decrease in step frequency would ultimately improve the participant's walk ratio and create a more efficient and stable gait pattern ready for a greater degree of safe community ambulation.

P1 did not increase MP velocity to the same degree as PP velocity following the RAS intervention. The participant continued to rely on a greater relative contribution from cadence to improve walking speeds that ultimately placed a ceiling on the participant’s high-level mobility. Using an increased cadence to obtain faster speeds is an unsustainable walking strategy that will limit walking endurance at this speed (107). P2 consistently demonstrated a difference between PP and MP walking speeds that exceeded NT values. RAS appeared to reduce both PP and MP walking velocity but caused a greater reduction in preferred velocity by comparison. This participant had consistently elevated levels of cadence during preferred walking, thus to obtain
an increased walking speed P2 relied on a more substantial increase in step length – a pattern that did not appear to change after the RAS intervention. Ultimately, RAS appeared to have a greater effect on preferred velocity over the course of the intervention for both participants, aligning with previous findings (19) and did not alter the inefficient methods both participants used to increase walking speed.

A commonly reported symptom in post-TBI gait is instability, reflected in an increased spatial and temporal step-to-step variability (63). Step length variability of individuals with TBI has been found to be larger than NT values during PP and MP walking conditions while temporal variability was found to be greater than NT values at MP walking conditions only (63). In the present study, changes in temporal and spatial variability appear to be linked to changes in walk ratio. An optimal walk ratio is related to improved dynamic control of gait and the consistency of the stepping pattern (107,108). As P1 increased their walk ratio towards NT values, temporal and spatial variability decreased, and stride width variability increased, all markers of improved timing and stability. Reductions in temporal variability have been detailed previously following RAS training interventions in individuals with PD; however, in some cases, changes in variability did not remain after a 1-month follow-up (169,252). In the present case series, the improvement P1 achieved in temporal and spatial variability were retained at follow-up, which offers the hypothesis that improvements in gait stability can be retained after training with RAS. Following RAS, P2 increased temporal and spatial variability during PP walking and decreased variability during fast walking. The increase in PP variability is likely a byproduct of slower walking speed and a deviation from the optimal step length to cadence ratio (107).

Step width has been shown to be greater in individuals post-TBI (58). Walking with a broader and shorter step length is commonly associated with a cautious gait and a compensation for instability (253). An overly narrow step width is also not ideal as it is associated with an increased likelihood of falling and energy expenditure (230,254,255). Previous studies noted that after 5 weeks of RAS training, individuals with PD displayed an increase in step width at a 17-week follow-up, even though changes were not detected immediately after the intervention (256). The duration and intensity of this RAS training regime were greater than the present study and the length of follow-up allowed for a more passage of time between the intervention and
follow-up assessment (256). Overall, it appears that improvements in step width were not notable following a RAS intervention and assessment period of this nature in individuals with TBI, which aligns with the findings of Kim et al. (135) in adolescents recovering from ABI.

Past work in stroke and TBI populations have determined that swing time ratio is particularly resistant to gait interventions (19,58). The duration of a RAS intervention can influence the degree of gait symmetry improvement (59). In the present study, P1 improved PP temporal and spatial symmetry, but appeared to increase temporal asymmetry once again at follow-up. Using visual cues to reinforce symmetrical walking would be easier for a participant to accomplish on their own, while replicating external auditory cueing during day-to-day walking would be more difficult (218). Thus, the retention in spatial, but not temporal, symmetry may be more feasible to sustain after the completion of the RAS training. P2 demonstrated a reduction in spatial symmetry during both walking conditions, however after the intervention, these improvements were lost. Evidently, retention of spatial symmetry can vary between participants who initially experience improvements after RAS. P2 also showed increased temporal asymmetry after the RAS intervention, a finding that is likely associated with a reduced walking speed (258). Patterson et al. (259) concluded that PP velocity was negatively associated with temporal asymmetry but not spatial asymmetry in community ambulating individuals post-stroke.

Finally, dual-task effect uncovered some interesting findings related to RAS training. According to Maclean et al. (260), as P1 improved single-task gait stability, walking should have become more autonomous, alleviating more cognitive resources to be allocated to the cognitive task. However, at baseline and post-training assessments, P1 increased speed and decreased stability during dual-task walking compared to single-task walking. This pattern has been previously described in PD as a risky adaptation contrasting the NT "posture first" adaptation (222). In this risk-accepting dual-task strategy, the retention of gait speed is given greater emphasis than stability with the introduction of a secondary task while walking (222). The lack of improvement in the cognitive task after RAS can be attributed to the difficulty this participant had with the subtraction task. By the 3-week follow-up, P1 began to demonstrate an ability to walk and talk at a fast speed at no expense to gait stability, which could serve this participant well while ambulating in the community.
P2 increased gait speed and stability during dual-task compared to single-task walking. It is difficult to pinpoint exactly why this change occurred; possibly a counting task could have imposed a rhythm and order to the participant's gait cycle (260) or perhaps the dual-task conditions were most similar to walking and attending to a metronome, which is the basis of the RAS gait training program. At baseline, the number of correct subtractions was less than after training with RAS and at the 3-week follow-up, suggesting that cognitive dual-task performance improved. One limitation of the present dual-task analysis is that the cognitive task (speech) has an artico-motor component. Yardley et al. (261) have shown that speaking during a counting backward task can change postural sway separately of the attention detriment associated with the cognitive dual-task.

At baseline, both participants had CB&M scores similar to individuals receiving acute care for TBI (188). After the RAS intervention, CB&M scores improved, suggesting that RAS can improve high-level mobility associated with community integration (65,188). At baseline, P1 had a 6MWT distance less than individuals at admission to a post-acute rehabilitation centre, as reported by Mossberg and co-authors (249). After the RAS intervention, P1 demonstrated an increased walking distance. P1 built upon the increased walking endurance at the 3-week follow-up assessment by increasing the distance walked with little change in reported exertion, compared to the post-intervention assessment. This finding suggests that the participants PP walking speed achieved after the RAS intervention (noted on the pressure sensitive mat) was sustainable, as the participant walked at a similar speed during the 6MWT at follow-up. It is essential to assess the sustainability of preferred walking speeds using the 6MWT because walking assessments occurring over shorter walking durations can overestimate preferred walking speeds at greater distances (262). P2 did not change walking distance after the RAS intervention; however, during the baseline assessment, a 1 minute break was taken. The participant reduced 6MWT speeds between baseline and post-training assessments (251). At the post-training walk, P2 did not experience the same level of fatigue that caused the participant to stop during the baseline assessment. This demonstrates an ability to select and sustain a more optimal speed after the RAS intervention, thereby decreasing energy expenditure and improving the prospects of community integration.
A limitation of this study is the restricted generalizability due to a sample size of 2 that included only males and a narrow scope of gait impairments (i.e., able to ambulate for 10 meters without assistance). Individuals in the present study were recruited from the community as a result gait compensations and adaptations may have been developed in the time since injury, which may limit the applicability of these findings to a more acute TBI setting. Additionally, a lack of kinematic, kinetic, electromyographic (EMG), or neuroimaging analysis limits the discussion to exclusively spatiotemporal findings and may cause our study to overlook significant gait impairments or effects of training (48,57,61,135). Furthermore, the reliance on a NMT for the delivery of the RAS limits the comparison to other home-based RAS intervention studies (76). Another limitation of the present study surrounds rhythm ability, as it has been demonstrated that beat perceptibility may influence an individual’s responsiveness to RAS (263). No assessment of rhythm perception abilities such as the Beat Alignment Test was conducted in the present study (264). Finally, the audio-motor component of the dual-task and lack of cognitive dual-task cost calculations limits the current findings. In conclusion, this case series demonstrates the feasibility of RAS to address many components of TBI-related gait impairments. In a large-scale RCT, these spatiotemporal outcomes and clinical measures should be used to compare RAS with conventional gait training. These findings, in harmony with a wealth of prior research, stress the importance of assessing walking under a variety of motor and motor-cognitive conditions using both spatiotemporal and clinical measures to ensure translatable improvements in gait to recuperate community walking. There is an increasing number of at-home RAS devices available to people with neurological disorders (265). These rhythm-based gait interventions can empower PD and stroke patients to take a more active role in their rehabilitation. TBI-related RAS research needs to be ready to reap all the benefits of this new technology, so therapists can confidently advise those with TBI about the safest and most beneficial application of this gait training technique.
4 General discussion

The objectives of the first study were: (1) to gain a better understanding of longitudinal changes in gait in the first year post-TBI, (2) to define gait abnormalities spatiotemporally based on time post-injury and patient characteristics, such as injury severity, and (3) to determine the relationship between spatiotemporal impairments and community integration over the course of recovery. With this knowledge, we intended to explore the feasibility of RAS as a gait training technique to address the gait abnormalities we described as persisting after the first-year post-TBI.

4.1 Summary of findings and rehabilitation implications

4.1.1 Longitudinal analysis of spatiotemporal gait following traumatic brain injury

Motor recovery after TBI is a time-dependent biological phenomenon (3,8,14,24–29,31,35,43). Most motor improvements occur within 6 months to a year after injury (3,24,27,35). The time it takes to achieve independent walking has been previously described (3,24,27), yet the time it takes to achieve a safe, efficient, stable, and autonomous gait pattern is less understood. If patients and therapists have a better understanding of when to expect particular spatiotemporal variables to improve, plateau, or diminish post-injury, specific rehabilitation plans and environmental adaptations can be established to improve an individual's independence and propensity for community integration long-term.

In a longitudinal analysis of spatiotemporal gait following TBI, we identified distinct patterns of change over time and specific features that distinguish individuals classified in different severity groups. Our analysis concluded that measures of forward progression, including walking speed, step frequency, and step length, demonstrate significant improvement early post-injury. One exception to this pattern of change was MP step length, as no significant change was noted over time for this measure. This finding appears to be driven by the least severely injured group, as this group exhibited a reduction in step length over time. At 2 months post-injury, this group relied on a step length that exceeded the upper 95% confidence limit of NT controls (215). An exaggerated step length caused a disruption of gait timing and stability as indicated by the high temporal variability noted in this group at the 2-month assessment. This confirms a well-established finding common to gait post-TBI, that stability should always be taken into
consideration, even in the presence of a normal walking speed (66). All severity groups displayed velocities and step lengths (PP and MP) that were the same as the NT sample after 1 year of recovery. However, all groups had an average cadence that was significantly lower than age-matched reference values (215). Individuals with an LPTA between 1-7 days demonstrated lower PP cadence than the sample of NT controls. Following TBI, a reduced cadence has been described as a compensation for greater instability while walking (58).

There was no significant effect of time or injury severity on walk ratio post-injury. While walking at preferred speeds, the least severely injured group employed a PP walk ratio that was consistently higher than groups sustaining more severe brain injuries. Over the first-year post-injury, the most severely injured group demonstrated a consistent increase in PP walk ratio. This observation suggests that this severity group demonstrated a greater rate of change in step length than cadence, while the opposite is true for individuals with a LPTA between 1-4 weeks. By 1 year post-injury, when compared with NT controls, individuals with the shortest and longest duration of post-traumatic amnesia had higher PP walk ratios than controls. This finding suggests that gait efficiency, automaticity, and timing may be compromised in order to prioritize gait stability (204). However, given that values reported for each LPTA group at 1 year post-injury fell within values reported for NT individuals walking on level surfaces (214,216), these finding should be interpreted with caution.

Although measures of forward progression demonstrated significant improvement post-injury, these changes in step length, cadence, and velocity did not appear to translate to significant improvements in step-to-step variability. During PP walking, the least severely injured group had relatively little change in step length variability or step time variability throughout the first year. Individuals experiencing more severe injuries appeared to demonstrate a larger initial PP step-to-step variability. In some cases, these individuals were unable to reduce temporal variability to NT values by the 1 year assessment. Ultimately, these varying patterns of change over time resulted in an effect of injury severity for measures of PP step time variability and step length variability. Although individuals with the shortest LPTA duration did not appear to demonstrate any issues related to gait stability during PP walking conditions, when tasked with walking at MP speeds, this group had step time variability and step length variability values that were
similar to more severely injured individuals (LPTA >4 weeks). These findings align with Niechwiej-Szwedo et al. (63), further emphasizing not only the importance of assessing all 3 components of step-to-step variability but also assuring that these spatiotemporal features are studied under a variety of walking conditions (72). To address issues related to step-to-step variability, a gait intervention that optimizes the regularity and trajectory of motor movement should be explored. Three weeks of RAS has been shown to reduce the timing variability in muscle activation in the tibialis anterior, vastus lateralis, and gastrocnemius muscles and reduce bilateral asymmetry in individuals with PD (236,237). Activation patterns in many of these muscles have recently been characterized as abnormal in chronic TBI populations (61), further endorsing the applicability of this gait training technique.

As previously mentioned, issues related to gait instability appear to affect individuals following TBI regardless of injury severity. Inness et al. (65) demonstrated that instability after brain injury is directly related to reduced community integration, which is the causal link between impairment and reduced quality of life (211). PP step time variability values at 5 months post-injury displayed a moderate negative correlation with CIQ total scores at 5 months post-injury. This concurrent correlation emphasizes the importance of addressing instability issues during post-injury rehabilitation. If these issues are unaddressed, individuals may be unable to fulfill roles at home, work, or in the community immediately post-injury. Furthermore, in the early time window post-injury, individuals should strive to establish effective environmental and social supports to succeed long-term after brain injury. If gait instability is an issue during this sensitive time, this could impede an individual’s ability to establish these supports, ultimately compromising long-term quality of life outcomes. If instability is associated with reduced community integration in the earliest months post-TBI, accommodations and supports (i.e., planning excursions with a family member or friend to decrease the risk of falls and increase walking confidence) should be made available to empower individuals to pursue life-enriching activities.

During PP and MP walking conditions, there was a significant effect of injury severity on temporal symmetry (i.e., swing time ratio). However, an effect of injury severity was only displayed for spatial symmetry (i.e., step length ratio) during MP walking conditions. Related to
gait variability, symmetry issues appeared most pronounced in the group with an LPTA >4 weeks (73,268). Although all 3 groups experienced a reduction in bilateral differences in step times throughout recovery, it appears that the most severely injured group no longer experienced improvements in temporal symmetry between 5 and 12-month assessments. This plateau in recovery not only reflects patterns of change seen in step time variability (73,268) but also reinforces findings made by Walker et al. (3) which reported a plateau in hemiparetic gait recovery at 6 months post-TBI. By 12 months post-injury, the most severely injured group had PP temporal symmetry values that were larger than NT controls. To date, few gait interventions studies have used symmetry outcomes (59,81,83), as greater emphasis is often placed on restoration of forward progression. In a longitudinal analysis of gait symmetry post-stroke, Patterson et al. (220) postulated that current inpatient stroke rehabilitation may prioritize the achievement of independence through restoration of speed and stability, with less emphasis placed on symmetry-related goals.

A widened step width is a gait deviation that is known to occur following TBI (57,58). Similar to the reduction in cadence, a broadening of the base of support is believed to compensate for inherent instability while walking (58). The most severely injured group demonstrated significantly larger step widths than the other severity groups. The most severely injured group was unable to reduce this increased step width over the course of recovery as these values remained higher than those reported in the NT samples at the 1 year assessment (63). The 2 most severely injured groups had a higher step width at MP compared to the sample of NT controls, indicating that faster walking speeds places a greater strain on gait stability.

Similar to the correlation between step time variability and community integration, step width demonstrated a strong negative correlation with CIQ total and home sub-scale scores. A wider step width as early as 5 months post-injury was correlated with reduced community integration scores 2 years after injury. This correlation persisted as a wider step width at 12 months was also correlated with reduced community integration at 2 years post-injury. An increased step width has previously been associated with falling and a fear of falling while walking in older adults (110). Thus, adopting a wider step width following a TBI may be a stabilizing fear-based adaptation, while step-to-step variability has no stabilizing value and thus in theory is unlikely to
be associated with fear of falling (110). Whether the association between step width and limited community integration is based on an increased number of falls, a fear of falling, or both, this question requires further exploration. Many of the ideas put forth surrounding increased caution during post-TBI gait resemble some of the conclusions drawn by McFadyen et al. (66) in 2003. In an obstacle crossing study, high-functioning individuals 2 to 6 months post-TBI displayed cautious gait patterns despite seemingly good recovery (median walking speed = 145 cm/s). The authors proposed that increased instability, decreased sensory control, or decreased confidence levels due to anxiety generated earlier in recovery could be attributed to the cautious adaptations (66). If stability is an issue for an individual as early as 5 months post-injury, care providers should recognize the potential long-term impact this walking impairment could have on an individual's quality of life. Long-term care providers and social-support staff should provide suitable environmental adaptations and coping strategies to address these concerns, with the ultimate aim of restoring pre-injury levels of community integration.

The dual-task effect demonstrated a greater degree of impairment as time since injury increased. At the 2-month assessment, dual-task performance varied greatly between groups of different injury severity. The least severely injured group walked at a faster speed while dual-tasking than single-tasking. By comparison, more severely injured groups demonstrated a greater negative dual-task effect suggesting that single-task walking was faster than dual-task walking. Over time, all groups demonstrated an increasingly negative dual-task effect. Similar to the findings noted by Haggard et al. (82), improvements in single-task walking performance following brain injury did not occur at the same rate as improvements made in dual-task performance. The present study’s findings suggest that complete gait automaticity may not be restored to pre-injury levels after one-year. Issues related to dual-tasking following TBI may be related to impairments in attention or executive functioning (120). There is also the possibility that impairments could be associated with a higher cognitive demand required during normal walking due to increased instability, resulting in a constant need to monitor step-to-step control (120). Efforts have been made to improve dual-task performance following ABI through dual-task training (142). After randomizing participants to receive dual-task training or a null control, Evans et al. (142) reported a difference in dual-task performance in the intervention group compared to controls.
The current study made several novel contributions to the field of TBI gait research. As a longitudinal spatiotemporal analysis of gait, the current findings provided added detail to the present understanding of motor recovery post-TBI (35). Many of the distinct patterns of change identified in this study align with previous longitudinal characterizations of early gait recovery in adults and children post-TBI (28,29,31,35,56,82,93,124) and results for the comparison with NT controls at 12 months align with previous cross-sectional studies (58,63,67,75,120). This is the first time that step-to-step variability, swing time symmetry, walk ratio, step width, and dual-task effect on velocity have been studied longitudinally in adults with TBI. Furthermore, by grouping participants by injury severity, this study’s findings built upon previous work that has used injury severity (i.e., LPTA) as a guiding predictor of motor outcome (15). McFadyen et al. (66) called for a greater number of studies to analyze the association between LPTA and gait performance. In the 2003 study of 10 high-functioning individuals early post-TBI, LPTA was correlated with the level of toe clearance and gait speed of the lead limb during obstacle avoidance (66). Findings from the present study help clarify the association between injury severity and gait performance during unobstructed walking. The final portion of this analysis supplements past work exploring the relationship between mobility and community integration (65,86). This study is the first to compare spatiotemporal variables longitudinally with community integration outcomes and builds upon previous cross-sectional studies (125).

4.1.2 Feasibility of a rhythmic auditory stimulation gait training intervention in community-dwelling adults after traumatic brain injury

In the second manuscript, we assessed the feasibility of RAS as a gait training technique in community-dwelling adults after TBI. We designed this study with the intention of addressing a gap in the literature surrounding the application of RAS as a gait training technique post-TBI. In the present study, both participants experienced a change in walking speed over the course of the intervention. For the first participant, faster speeds were obtained by training with a frequency set above the participant’s baseline cadence. A concurrent improvement in step length, cadence, and walk ratio also occurred. The second participant reduced unsafe walking speeds to below NT values following RAS training but retained a walk ratio that suggested a sub-optimal step length to cadence ratio. Both participants demonstrated an improvement in gait variability during MP
walking conditions; however, only the first participant showed improvement in gait variability during PP walking conditions. For both participants, stride width values remained relatively unchanged. A notable reduction in spatial symmetry occurred over the assessment period; however, the ability to retain these improvements at a 3-week follow-up assessment varied. RAS increased swing time ratio for both participants, except for P1 during PP walking. Even when temporal symmetry improved following the RAS intervention, these improvements appeared to subside by the 3-week follow-up. Dual-task performance improved over the course of the RAS intervention; however, the pattern of improvement varied between participants and across cognitive and motor outcomes.

This study made several novel contributions to TBI gait-related research. RAS has been previously used as a gait training technique in community-dwelling adults following TBI (76,143). This current study expanded on previous work by analyzing spatiotemporal measures including walk ratio, spatial symmetry, step-to-step variability, and dual-tasking. Furthermore, this is the first-time long-term carry-over effects of RAS training have been studied post-TBI to determine retention of this gait training technique. Finally, the integration of mobility and endurance outcome measures provides a new and more holistic approach to examine this gait intervention. The findings from this study build upon previous work related to RAS and TBI that noted improvement in velocity, cadence, step length, and temporal symmetry (76,143). This preliminary study suggests that other features of TBI gait can potentially be impacted by RAS training as demonstrated in individuals post-stroke and with PD (144,176).

4.2 Limitations
In the first manuscript, the sample size was relatively large for a longitudinal analysis; however, the participants may not have been representative of a heterogeneous population of adults with severe TBI. We assessed gait and community integration data of individuals capable of ambulating without the use of a gait aid for at least 2 of the 3 assessments. As such, lower functioning individuals after brain injury may have been less represented in the present study sample. Additionally, some individuals missed assessments over first year which may have affected the patterns of change over time and correlations described in the study. Many spatiotemporal features of gait and measures of community integration were compared and as a
result the conservative Bonferroni-Holm correction for multiple comparisons may have caused some significant relationships to go unreported. This statistical correction may have removed other findings such as the association between walking speed and CIQ productivity from the present analysis (125). In the second study, we examined the feasibility of RAS as a gait intervention in 2 individuals. Only individuals capable of attending 9 gait training sessions were able to participate in the study, which limits the generalizability of these findings to individuals with a baseline proficiency to ambulate for longer durations of time. Finally, both studies were only able to report on spatiotemporal variables and do not contain any information related to joint kinematics, kinetics, muscular activation, or neuroimaging. This limitation decreases the number of comparisons that can be made with previous studies in TBI literature (48,57,61,75,88) as well as recent studies in ABI and RAS interventions (135).

4.3 Future directions

4.3.1 Longitudinal analysis of spatiotemporal gait following traumatic brain injury

Future characterizations of the longitudinal change in gait following TBI could expand in several ways. Assessing the relationship between changes in cognition post-TBI (i.e., executive function, working memory, and attention (269)) or underlying brain tissue damage (36–38,48) in relation to walking ability could build upon previous research relating cognitive measures and neuroimaging with gait performance after TBI (48,101). Furthermore, comparing records of gait training intensity and duration between individuals in the first year post-injury would help explore the relationship between gait rehabilitation and spatiotemporal outcomes (19,270,271).

Another potential avenue of exploration involves studying spatiotemporal variables within individuals changing from PP to MP walking speeds. Williams et al. (57) demonstrated that increasing walking speed occurs differently for those with a severe brain injury than NT controls. Thus, exploring if this pattern changes over the course of the first-year post-injury could provide longitudinal context to these particular findings. In the future, a more comprehensive assessment of dual-task performance following brain injury should be conducted to take into consideration not only changes in walking velocity between single and dual-task, but also changes in gait stability such as step-to-step variability and step width. Assessing step-to-step variability under dual-task conditions has been a point of emphasis in PD research and could be another feature of dual-task walking to explore longitudinally following TBI (272). Future comparisons between
spatiotemporal measures and community integration should not be limited to the CIQ exclusively (205), and should incorporate measures of falls and fear of falling (87). Previous studies have also compared the Brain Injury Community Rehabilitation Outcome Scale (273) with mobility outcomes after TBI (86).

4.3.2 Feasibility of a rhythmic auditory stimulation gait training intervention in community-dwelling adults after traumatic brain injury

The feasibility of RAS established in this study will serve as the basis of a RCT examining the effects of RAS in TBI. Future studies should also characterize the effect RAS used in conjunction with conventional gait training in an acute inpatient setting, as most studies in TBI are limited to community-dwelling individuals (76) or individuals at least 6-months following injury and in long-term care facilities (143). A greater number of motor-cognitive and motor-motor measures should also be used in future studies to assess dual-task performance. Increasing the variety and number of dual-task outcome measures would build upon work related to walking and visual processing (i.e., the Stroop task) after TBI (67,81,120,274). In PD research, motor-motor dual-tasks are often used to gauge the effectiveness of RAS (144); however, to date no study has assessed the effect of RAS on motor-motor dual-tasking in the field of TBI. Finally, to add to the work of Kim et al. (135), an assessment of kinematic and kinetic measures of gait using 3DGA would provide a wealth of additional biomechanical information to characterize the effects of RAS. For future studies, an objective recording of the participants level of activity (i.e., Actigraph monitor) during training sessions would provide added information related to the intervention's feasibility (275). Furthermore, assessing the therapist’s perception of participant engagement could also provide insight into the level of acceptance of the intervention (276).

5 Conclusion

The spatiotemporal gait impairments that follow TBI have been detailed previously. The first of our 2 investigations used these studies as a guideline to conduct a longitudinal spatiotemporal gait analysis in the first year following TBI. Research shows that the most significant motor and cognitive recovery occurs early after injury; thus, understanding the changes that occur in the gait cycle during this period of heightened neurological flux opens an array of new avenues to explore gait interventions geared to address these gait abnormalities. Furthermore, the findings in
our study emphasize the link between community integration and mobility after TBI. Community reintegration is a point of emphasis for many individuals after brain injury and is linked with positive physical and mental health outcomes. Considering this, helping individuals obtain a fast, steady, and autonomous gait should be continually explored until interventions designed to address post-injury walking issues have been perfected.

RAS is a gait training technique currently understudied in the TBI population. Presently, reviews have documented that there is no one gait intervention to address spatiotemporal impairments after brain injury. However, many of the issues that individuals with brain injuries present with while walking are similar to impairments of individuals post-stroke and with PD, two neurological populations that have demonstrated the benefits of training with RAS. This current study along with previous efforts in TBI and RAS have provided preliminary evidence of the potential translatability of this intervention. Future work should continue to characterize gait abnormalities post-TBI, using time since injury and injury severity as descriptive tools to help clinicians and patients eventually apply interventions like RAS to their daily practice.
6 References


126. Frasca D. Multi-Tasking in Adults with Traumatic Brain Injury: Examining the Impact of Concurrent Motor and Cognitive tasks [Internet] [Ph.D.]. [Canada]: University of Toronto (Canada); 2015 [cited 2018 Apr 17]. Available from: http://search.proquest.com/docview/1758019228/abstract/3C87F6C383EA403BPQ/1


