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The variability of dual-task walking parameters using in-shoe inertial sensors in nonconcussed individuals: A randomized within-subject repeated measures design

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Abstract

Background and Aims: There is a need for high utility and portability, and cost-effective technologies that are suitable for assessing dual-task gait after experiencing a concussion. Current technologies utilized such as 3D motion capture and force plates are too complex and expensive for most practitioners. The aim of this study was to quantify the variability of dual-task walking gait parameters using in-shoe inertial sensors in nonconcussed individuals.

Methods: This was a randomized within-subject repeated measures design conducted within a sports laboratory. Twenty healthy, uninjured, nonconcussed participants were recruited for this study. Gait variables of interest were measured across three 2-min continuous walking protocols (12 m, 30 m, 1 min out and back) while performing a cognitive task of counting backward in sevens from a randomly generated number between 300 and 500. Testing was completed over three occasions separated by 7 days, for a total of nine walking trials. Participants completed the testing protocols in a randomized, individual order. The primary outcome was to determine the variability of dual-task walking gait parameters using in-shoe inertial sensors in nonconcussed individuals across three protocols.

Results: Three to four participants were allocated to each randomized protocol order. Regarding the absolute consistency (coefficient of variation [CV]) between testing occasions, no gait measure was found to have variability above 6.5%. Relative consistency (intraclass correlation coefficient [ICC]) was acceptable (>0.70) in 95% of the variables of interest, with only three variables < 0.70. Similar variability was found across the three testing protocols.

Conclusion: In-shoe inertial sensors provide a viable option for monitoring gait parameters. This technology is also reliable across different testing distances, thus offering various testing options for practitioners. Further research needs to be conducted to examine the variability with concussed subjects.

KEYWORDS
concussion, gait, inertial measurement unit

1 | INTRODUCTION

Concussions are an increasingly common mild traumatic brain injury that can occur during sport that are frequently missed or under-estimated resulting in individuals returning to sport earlier than they should. In some cases, this can increase the risk of sustaining a musculoskeletal injury[1,2] or lead to further brain damage if a second concussion is experienced in close proximity to the first concussive event.[3,4] To limit misdiagnosis, there is a need to have protocols that can assess the extent of the concussion experienced while also determining readiness for return to activity. Typical methods of assessing concussions are clinical assessments which consider physical and mental attributes such as balance and memory, respectively.[5] These assessments are generally tested as two separate elements, yet researchers have suggested that a dual task (DT) assessment that combines physical and mental testing provides a more accurate understanding of concussion than standalone walking and cognitive assessments.[6–9] For example, researchers have shown gait deficits to be more evident in concussed individuals during DT walking than single task (ST) walking.[6–9]

There is an abundance of research that has investigated the efficacy and utility of DT gait assessment in concussion diagnosis.[10–16] Much of the research in this area has used 3D motion capture (MOCAP) and force plate technology to determine the influence of concussion diagnosis on gait parameters.[10,11,14–19] A recent review, however, has pointed out that none of the typical gait parameters (e.g., gait velocity, stride length, etc.) measured by these devices were found to be sensitive enough to consistently determine differences between concussed and nonconcussed diagnoses.[20] It was speculated that environmental restrictions presented in a typical sports laboratory is a key limitation in using these devices, while it was also pointed out that there was an absence of reliability data on any of the outcome measures of interest, which is fundamental to interpreting findings and could explain the data variability or lack of sensitivity. Other limitations using such 3D MOCAP and force plate technology are portability, cost of the equipment, and the expertise and time required to process and analyze the data, which preclude concussion assessment outside of a well-funded research environment.

Inertial sensors are becoming a prevalent technology within clinical settings as it can be used to characterize gait performance among populations with a range of conditions that impair gait. The appeal of this technology is testing is not limited to a laboratory environment, which may improve the likelihood of natural gait being performed by patients if testing is performed with more familiar surroundings and thus allow for more accurate observations to be made by practitioners.[21,22] Inertial sensors have shown to be a reliable tool for identifying spatiotemporal gait parameters,[23] while also being reliable and valid in comparison to 3D MOCAP.[24,25] The environmental restrictions that arise from 3D MOCAP's limited field of capture are not as significant with inertial sensors given its portability. Assessing gait over a longer distance than the 8–10 m typically used for laboratory gait testing with fewer turns could provide a more accurate representation of an individual's natural gait due to minimizing the variability of gait parameters (i.e., influence of accelerations and decelerations).[26,27]

The advent of technologies such as inertial sensors may enable DT testing outside the lab given the portability of such devices. Inertial sensor technology has been used in a few studies to date with some promising results reported for average speed and stride length during DT locomotor activities.[9,28–31] However, the reliability has not been documented and there may be better placement of sensors than the lumbar and dorsum sites utilized in the research to date; the best placement for sensors has not been formally studied yet. For example, it would be interesting to determine if inertial sensors that quantify the foot-ground interaction (e.g., inner sole sensors) offer increased measurement accuracy in this area. Given this information, the primary aim of this study was to determine the test–retest reliability of DT walking gait parameters using in-shoe inertial sensors in non-concussed individuals. It was hypothesized that gait speed and stride length would show acceptable test–retest reliability, based on findings from similar investigations.[25,32] The secondary aim of this research was to determine if gait parameters are different across the 12 m, 30 m, and 1 min out and back testing conditions. It was hypothesized that the greater straight-line distances associated with the 1 min out and back protocol would be less variable than both the 12 and 30 m protocols, given that fewer turns would reduce the variability of data across the gait parameters of interest.[26] Understanding this variability in nonconcussed individuals will provide baseline data on gait parameters typically quantified and inform practitioners as to what the expected movement variability is with unaffected DT walking using inner sole inertial sensor technology. If found acceptable, this technology and protocol/s may provide viable assessment options that could result in higher utility of DT walking assessments in the diagnosis of concussion and assist with return to play after experiencing a concussion.

2 | METHODS

2.1 | Study design

This study used a within-subject repeated measures design, where participants performed a 2-min continuous walking protocol with in-sole inertial sensors placed in their shoe, while performing a cognitive task (DT) over three conditions: 12 m, 30 m, and 1 min out and back. The same session was completed over three testing occasions separated by 7 days. The order of testing conditions was randomly assigned to each participant. A repeated measures analysis was conducted on the raw data to determine whether between-day performance differed in terms of mean percent change, absolute consistency (coefficient of variation [CV]), and relative consistency (intraclass correlation coefficient [ICC]). The study followed CONSORT guidelines for reporting randomized trials.[33]

2.2 | Participants

Twenty participants (8 females/12 males) (age: 35.2 ± 16.1 year; height: 173.7 ± 10.8 cm; body mass: 75.0 ± 14.0 kg) participated in this study. Participants were of varying sporting backgrounds, ranging from regional sporting representatives to no current engagement in physical activity. Participants were required to be healthy and free of injury that would affect their normal gait movement at the time of testing. After being orally briefed on the methods and reading the information sheet, participants provided their signed informed consent before participating in this study. Participants were notified that they were free to withdraw from the study at any point. This research was approved by the Auckland University of Technology Ethics Committee (22/23).

2.3 | Procedures

Piloting was undertaken before data collection to establish how many trials of each protocol were needed. It was established that one trial of each condition was sufficiently accurate and reliable as there was minimal systematic change across three trials of each condition; therefore, the methodology only incorporated one trial of the three protocols that is, 2 min of 12 m, 30 m, and 1 min out and back.

Testing was conducted on an outdoor level surface. Wearing the same shoes and clothing that would not restrict natural gait, participants were required to attend three testing sessions. Testing sessions were conducted 7 days apart, at approximately the same time of day, under similar experimental conditions. During each testing session, participants performed 2-min continuous walking assessments while performing a cognitive task during the three protocols. The cognitive task involved participants, before initiating each trial, receiving a random number between 300 and 500 and counting backwards in sevens for the duration of each trial. This task has been commonly used as a cognitive task in similar investigations of DT locomotion within concussed and nonconcussed populations.[10,13,30,34,35]

For the 12 m and 30 m tests, the participants started at a cone. After being instructed to start, the participants began walking at a self-selected pace while performing the cognitive task toward a cone placed at 12 m and 30 m, respectively. There were no instructions provided regarding how many laps were to be completed, as the participants walked at a self-selected speed and thus traveled different distances. Upon reaching the second cone, participants either walked in a clockwise or anti-clockwise direction around the cone and returned to the start cone. This circuit was navigated for 2 min. Participants were free to choose which way to navigate the cone but were instructed to navigate the cones the same way throughout all the testing and over the three testing occasions.

For the 1 min out and back test, participants started at a cone. After being instructed to start, the participants began walking in a straight line at a self-selected pace while performing the cognitive task. After 1 min of continuous walking, the participant was instructed to turn around and head back towards the start for a further minute. There were no instructions provided regarding how much distanced was to be covered, as the participants walked at a self-selected speed and thus travelled different distances. For each of the testing conditions, participants were observed to ensure that their walking style remained consistent (e.g., not walking with hands in pockets). Approximately 2 min of rest were given between testing conditions, which is based on the time it takes to reset the equipment for the next trial. The order of testing conditions was randomized for each participant.

2.4 | Equipment

To quantify gait variables, two inertial measurement sensors (Plantiga Insoles) were placed in the participants' shoes. Inertial measurement sensors are a valid technology for measuring spatial-temporal gait parameters[21,36] that has been utilized to monitor gait performance among individuals with physiological conditions that may cause gait and balance impairments[21,37,38] Data were obtained at a sampling frequency of 416 Hz, time synchronized, and uploaded to a laptop computer following each testing occasion. Two cones were used for each respective test. The random number between 300 and 500 was generated using an online random number generator (random.org, Randomness and Integrity Services Ltd).

2.5 | Outcomes

The primary outcome was to determine the data variability of dual-task walking gait parameters using in-shoe inertial sensors in nonconcussed individuals across three protocols. Additional analysis was conducted to determine the variability in gait outcomes of interest: average walking speed (m/s), cadence (steps/min), average stride length (3D coordinates recorded at take-off time and landing time, measuring the distance between the coordinates [left/right/total]) (m), ground contact time (left/right/total) (ms), and double support (%). Each outcome was calculated using the associated Plantiga online software.

2.6 | Sample size

The sample size was selected based on sample sizes utilized in previous research with similar protocols.

2.7 | Randomization

Participants were allocated to a random allocation sequence of testing conditions through an online random list generator (random.org, Randomness and Integrity Services Ltd). The randomization was completed for each participant before the commencement of the first testing occasion. A single researcher (Courtney Mitchell) generated and assigned the randomized testing order for each participant.

2.8 | Statistical analysis

Mean and standard deviations were reported for participant characteristics and all variables and represent measures of centrality and spread of data. All data were analyzed using IBM SPSS statistical software package (version 28.0, IBM Corporation). Data were reported using 90% confidence limits (CL) and means. Each dependent variable was investigated between the first and second sessions and between the second and third sessions. A one-way analysis of variance (ANOVA) using repeated measures was used to determine whether between-day performance differed for each of the outcomes. To assess the systematic differences between testing sessions one to two and two to three, dependent *t*-tests were used. For each comparison, statistical significance was set at $p < 0.05$.[39,40] Absolute consistency between sessions was assessed using a specifically designed Excel (Microsoft 365, version 2202, Microsoft Corporation) spreadsheet from sportsci.org[41,42] to quantify reliability. Relative consistency using test-retest correlations was measured via ICC using a two-way random model and average measures.[43] CVs of less than 10% were deemed acceptable as a percent of typical error.[40] Classification of ICC was deemed as follows: "very poor" (<0.20), "poor" (0.20–0.49), "moderate" (0.50–0.74), "good" (0.75–0.90), or "excellent" (>0.90).[44]

3 | RESULTS

3.1 | Participant flow

All participants participated in each testing occasion; no participants were excluded after allocation (Figure 1). No protocol deviations were necessary.

3.2 | Participant recruitment

Participants were recruited from February 2021 to April 2021. Participants attended the sports laboratory for three testing occasions across 3 weeks, with the testing being separated by 7 days.

Means, SD, % change in the mean CV and the ICC for the three protocols can be seen in Tables 1–3. In terms of the 12 m means and SD, there seemed to be little evidence of any systematic variation. The percent change in mean from Day 1–2 ranged from −2.1% to 2.8% and Day 2–3 −0.7% to 0.9% for the variables of interest. The average percent change across all variables between testing occasions were 1.67% and 0.59%. With regard to the absolute consistency between testing occasions, CVs ranged from 2.3% to 4.8%, the largest variability was associated with average gait speed on both Day 1–2 (CV = 4.8%) and Day 2–3 (CV = 4.6%). The relative consistency (ICC) of the variables of interest ranged for the most part between 0.80 and 0.94. Only one variable was found to have an ICC less than 0.80 (left average stride length Day 2–3: ICC: 0.69).

There was little evidence of any systematic variation for the 30 m protocol. The percent change in mean from Day 1–2 ranged from −1.8% to 2% and Day 2–3 −2.0% to 0.9%. The average percent change across all variables were 1.17% and 0.9%. In terms of the absolute consistency between testing occasions, CVs ranged from 1.7% to 6.3%. Double support had the largest variability on Day 1–2 (CV = 5.2%) and left average stride length had the largest variability on Day 2–3 (CV = 6.3%). The relative consistency (ICC) of the variables of interest ranged for the most part between 0.75 and 0.94. Only one variable was found to have an ICC less than 0.75 (left average stride length Day 2–3: ICC 0.53).

Regarding the 1 min out and back protocol, no systematic variation was evident, the Day 1–2 and Day 2–3 percent changes in mean ranged from −2.4% to 1.3%, and −1.6% to 3.5%, respectively.
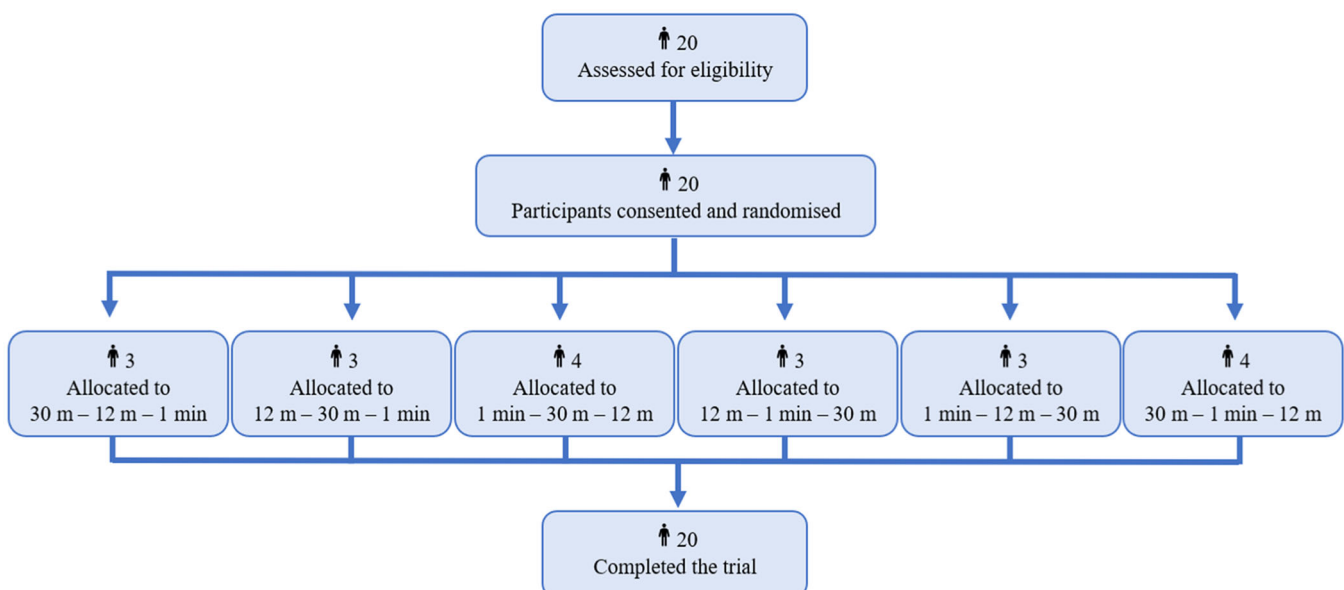

FIGURE 1 Participant flow diagram.

TABLE 1 Descriptive statistics for 12 m protocol.

	Mean (± SD)			% change of mean		CV		ICC		p	
	Day 1	Day 2	Day 3	Day 1–2	Day 2–3	Day 1–2	Day 2–3	Day 1–2	Day 2–3	Day 1–2	Day 2–3
GS	1.20 (0.13)	1.23 (0.12)	1.23 (0.11)	2.8 (0.2 to 0.55)	−0.5 (−2.9 to 2.0)	4.8 (3.8 to 6.6)	4.6 (3.6 to 6.3)	0.83 (0.66 to 0.92)	0.80 (0.62 to 0.90)	0.094	0.726
CAD	105.25 (4.55)	107.08 (6.25)	106.38 (7.10)	1.1 (−0.2 to 2.4)	−0.7 (−2.0 to 0.6)	2.4 (1.9 to 3.3)	2.5 (2.0 to 3.4)	0.83 (0.67 to 0.92)	0.87 (0.73 to 0.94)	0.189	0.382
SL											
Total	1.36 (0.11)	1.38 (0.11)	1.37 (0.10)	1.4 (−0.2 to 3.0)	−0.3 (−1.9 to 1.4)	2.9 (2.3 to 3.9)	3.1 (2.5 to 4.3)	0.89 (0.78 to 0.95)	0.85 (0.71 to 0.93)	0.142	0.683
Left	1.35 (0.11)	1.37 (0.11)	1.35 (0.12)	1.4 (−0.1 to 3.0)	−1.0 (−3.5 to 1.5)	2.9 (2.3 to 3.9)	4.8 (3.8 to 6.6)	0.89 (0.77 to 0.95)	0.69 (0.43 to 0.84)	0.139	0.497
Right	1.37 (0.12)	1.39 (0.11)	1.39 (0.11)	1.2 (−0.4 to 2.9)	−0.2 (−1.8 to 1.4)	3.0 (2.4 to 4.1)	2.9 (2.3 to 4.0)	0.88 (0.76 to 0.94)	0.87 (0.74 to 0.94)	0.229	0.697
GCT											
Total	704.70 (56.96)	689.25 (48.96)	693.05 (49.51)	−2.1 (−3.8 to −0.4)	0.6 (−0.7 to 1.9)	3.2 (2.5 to 4.4)	2.4 (1.9 to 3.3)	0.85 (0.70 to 0.93)	0.90 (0.80 to 0.95)	0.037*	0.476
Left	704.10 (55.85)	689.00 (48.18)	695.35 (53.74)	−2.1 (−3.7 to −0.4)	0.9 (−0.6 to 2.4)	3.1 (2.5 to 4.3)	2.8 (2.2 to 3.8)	0.85 (0.70 to 0.93)	0.87 (0.74 to 0.94)	0.039*	0.334
Right	704.60 (57.67)	689.90 (50.63)	692.35 (49.03)	−2.0 (−3.7 to −0.3)	0.4 (−0.9 to 1.7)	3.2 (2.5 to 4.4)	2.3 (1.8 to 3.2)	0.86 (0.71 to 0.93)	0.91 (0.81 to 0.96)	0.045*	0.637
DS	22.21 (2.97)	21.98 (2.77)	22.15 (2.91)	−0.9 (−3.1 to 1.2)	0.7 (−1.1 to 2.5)	4.0 (3.2 to 5.6)	3.3 (2.6 to 4.6)	0.92 (0.82 to 0.96)	0.94 (0.87 to 0.97)	0.424	0.457
Overall average				1.67	0.59						

Note: Data are mean ± SD of each variable. Abbreviations: CAD, cadence (steps/min); CL, confidence limit set at 90%; difference between sessions presented as the percent (%) difference (range) with CL lower and upper values; CV, coefficient of variation; DS, double support (%); GCT, ground contact time (ms); GS, gait speed (m/s); ICC, intraclass coefficient; SL, stride length (m).
*p < 0.05.

TABLE 2 Descriptive statistics for 30 m protocol.

	Mean (± SD)			% change of mean		CV		ICC		p	
	Day 1	Day 2	Day 3	Day 1-2	Day 2-3	Day 1-2	Day 2-3	Day 1-2	Day 2-3	Day 1-2	Day 2-3
GS	1.28 (0.15)	1.30 (0.12)	1.28 (0.13)	2 (−0.3 to 4.4)	−1.3 (−4.0 to 1.4)	4.3 (3.4 to 5.9)	5.1 (4.0 to 7.1)	0.86 (0.71 to 0.93)	0.75 (0.53 to 0.88)	0.195	0.423
CAD	107.65 (6.85)	108.72 (7.01)	109.04 (5.79)	1.0 (−0.8 to 2.8)	0.4 (−0.7 to 1.5)	3.3 (2.6 to 4.6)	2.0 (1.6 to 2.8)	0.76 (0.54 to 0.88)	0.90 (0.79 to 0.95)	0.332	0.890
SL											
Total	1.42 (0.12)	1.42 (0.12)	1.41 (0.12)	0.5 (−1.0 to 2.0)	−1.1 (−3.0 to 0.9)	2.7 (2.2 to 3.7)	3.7 (2.9 to 5.1)	0.91 (0.81 to 0.96)	0.81 (0.63 to 0.91)	0.595	0.370
Left	1.40 (1.12)	1.42 (1.12)	1.39 (1.3)	0.9 (−0.5 to 2.3)	−2.0 (−5.2 to 1.3)	2.6 (2.1 to 3.6)	6.3 (5.0 to 8.7)	0.92 (0.82 to 0.96)	0.53 (0.2 to 0.75)	0.314	0.306
Right	1.43 (0.13)	1.44 (0.12)	1.42 (0.12)	0.7 (−0.8 to 2.3)	−1.2 (−3.1 to 0.7)	2.8 (2.3 to 3.9)	3.6 (2.8 to 4.9)	0.90 (0.80 to 0.95)	0.84 (0.68 to 0.92)	0.456	0.278
GCT											
Total	685.85 (56.32)	673.25 (44.39)	676.00 (47.98)	−1.7 (−3.3 to −0.1)	0.4 (−0.5 to 1.3)	3.1 (2.4 to 4.2)	1.7 (1.4 to 2.4)	0.85 (0.70 to 0.93)	0.94 (0.88 to 0.97)	0.076	0.461
Left	686.05 (55.03)	672.95 (43.03)	679.15 (51.77)	−1.8 (−3.4 to −0.2)	0.9 (−0.5 to 2.2)	3.0 (2.4 to 4.2)	2.4 (1.9 to 3.4)	0.85 (0.70 to 0.93)	0.89 (0.78 to 0.95)	0.060	0.274
Right	686.35 (58.32)	673.40 (45.70)	674.15 (49.33)	−1.8 (−3.5 to 0.0)	0.1 (−0.9 to 1.1)	3.2 (2.6 to 4.5)	1.8 (1.4 to 2.5)	0.85 (0.69 to 0.93)	0.94 (0.88 to 0.97)	0.081	0.848
DS	21.23 (3.18)	21.08 (2.70)	21.27 (3.03)	0.1 (−2.6 to 2.9)	0.7 (−1.2 to 2.7)	5.2 (4.1 to 7.2)	3.6 (2.9 to 5.0)	0.88 (0.76 to 0.94)	0.94 (0.87 to 0.97)	0.896	0.428
Overall average				1.17	0.9						

Note: Data are mean ± SD of each variable. Abbreviations: CAD, cadence (steps/min); CL, confidence limit set at 90%; difference between sessions presented as the percent (%) difference (range) with CL lower and upper values; CV, coefficient of variation; DS, double support (%); GCT, ground contact time (ms); GS, gait speed (m/s); ICC, intraclass coefficient; SL, stride length (m).

TABLE 3 Descriptive statistics for 1 min out protocol.

	Mean (± SD)			% change of mean		CV		ICC		p	
	Day 1	Day 2	Day 3	Day 1–2	Day 2–3	Day 1–2	Day 2–3	Day 1–2	Day 2–3	Day 1–2	Day 2–3
GS	1.24 (0.15)	1.26 (0.14)	1.25 (0.13)	1.3 (−0.6 to 3.2)	−0.6 (−2.8 to 1.6)	3.5 (2.8 to 4.8)	4.1 (3.3 to 5.7)	0.92 (0.84 to 0.96)	0.87(0.74 to 0.94)	0.302	0.612
CAD	106.95 (6.63)	107.57 (6.47)	105.62 (7.70)	0.3 (−1.0 to 1.6)	−1.6 (−2.9 to −0.3)	2.4 (1.9 to 3.4)	2.5 (1.9 to 3.4)	0.86 (0.71 to 0.93)	0.89 (0.77 to 0.95)	0.683	0.038*
SL											
Total	1.40 (0.14)	1.41 (0.13)	1.40 (0.13)	0.7 (−0.5 to 1.9)	−0.3 (−1.9 to 1.4)	2.2 (1.7 to 3.0)	3.0 (2.4 to 4.1)	0.95 (0.90 to 0.98)	0.90 (0.80 to 0.95)	0.353	0.760
Left	1.38 (1.3)	1.39 (0.13)	1.38 (0.11)	1.0 (−0.3 to 2.2)	−0.6 (−2.1 to 1.0)	2.3 (1.8 to 3.1)	3.0 (2.4 to 4.1)	0.95 (0.89 to 0.98)	0.89 (0.78 to 0.95)	0.208	0.484
Right	1.42 (0.14)	1.42 (0.14)	1.43 (0.13)	0.6 (−0.7 to 1.8)	0.4 (−1.4 to 2.3)	2.3 (1.8 to 3.2)	3.4 (2.7 to 4.7)	0.95 (0.90 to 0.98)	0.88 (0.76 to 0.94)	0.475	0.694
GCT											
Total	690.90 (58.03)	673.25 (44.39)	690.00 (50.23)	−2.4 (−4.8 to 0.0)	3.5 (1.6 to 5.4)	4.6 (3.6 to 6.4)	3.4 (2.7 to 4.7)	0.67 (0.40 to 0.83)	0.79 (0.59 to 0.90)	0.093	0.004
Left	691.80 (58.29)	685.20 (45.42)	697.40 (49.69)	−0.8 (−2.2 to 0.5)	1.8 (0.6 to 2.9)	2.5 (2.0 to 3.4)	2.1 (1.7 to 2.9)	0.91 (0.81 to 0.96)	0.92 (0.83 to 0.96)	0.257	0.018*
Right	689.90 (58.66)	685.15 (47.05)	696.80 (51.35)	−0.6 (−2.0 to 0.8)	1.7 (0.6 to 2.8)	2.6 (2.0 to 3.6)	2.0 (1.6 to 2.8)	0.90 (0.80 to 0.95)	0.93 (0.85 to 0.97)	0.422	0.019*
DS	21.03 (3.33)	21.20 (3.03)	21.86 (3.35)	1.0 (−1.9 to 4.0)	3.0 (1.1 to 5.0)	5.5 (4.3 to 7.6)	3.5 (2.8 to 4.9)	0.89 (0.77 to 0.95)	0.95 (0.90 to 0.98)	0.668	0.016*
Overall average				0.97	1.5						

Note: Data are mean ± SD of each variable. Abbreviations: CAD, cadence (steps/min); CL, confidence limit set at 90%; difference between sessions presented as the percent (%) difference (range), with CL lower and upper values; CV, coefficient of variation; DS, double support (%); GCT, ground contact time (ms); GS, gait speed (m/s); ICC, intraclass coefficient; SL, stride length (m).

*$p < 0.05$.

TABLE 4 Range of reliability measures across variables within each testing protocol.

	Change in mean %	CV	ICC
12 m	−2.1 to 2.8	2.3 to 4.8	0.80 to 0.94 (0.69)
30 m	−1.8 to 2	1.7 to 6.3	0.75 to 0.94 (0.53)
1 min	−2.4 to 3.5	2.0 to 5.5	0.79 to 0.95 (0.67)

Abbreviations: CV, coefficient of variation; ICC, intraclass coefficient—ICC values presented as range (outlier).

The average percent change across all outcomes of interest between testing occasions was 0.97% and 1.5%. With regard to absolute consistency between testing occasions, CVs ranged from 2.0% to 5.5%. Double support had the largest variability for Day 1–2 (CV = 5.5%) and average gait speed had the largest variability for Day 2–3 (CV = 4.1%). The relative consistency (ICC) of the variables of interest ranged for the most part between 0.79 and 0.95. A single variable was found to have an ICC less than 0.79 (average stride length Day 1–2: ICC: 0.67).

Summary data for the three testing protocols can be seen in Table 4. As can be observed from the table, the differences between the variables of interest were minimal, with all percent changes in means < 3.6%, CV < 6.4% and ICCs for the most part > 0.75.

4 | DISCUSSION

DT assessments of concussion are common in the literature and typically use 3D MOCAP and force plate technology. Most of this technology is inaccessible and unaffordable to most practitioners, hence there is a need to find technology and protocols that are of high utility and portability, and cost-effective. One such technology might be the use of in-shoe inertial sensors. Before determining its utility in quantifying concussed gait parameters, it would be prudent to determine the expected variability associated with nonconcussed gait, this contention providing the focus of this research. The main findings were (1) in terms of absolute consistency, no measure was found to have variability above 6.5%; (2) the relative consistency was acceptable (>0.70) in 95% of the variables that is, only three variables were < 0.70; and, (3) the variability across the three protocol distances was similar. With regard to the hypotheses, that average gait speed and stride length would have the least variability, it was found that all outcome measures had acceptable test-retest reliability. Furthermore, the hypothesis that the longer straight-line distance associated with the 1 min out and back protocol would have the least variability was unfounded.

Coefficients of variation are deemed acceptable when they are less than 10%.[45] None of the variables in this study were greater than 10%; in fact, all were less than 6.5%, indicating that the measures are relatively stable between testing occasions. Research groups who have investigated similar DT walking protocols using other technologies have not reported the reliability of their respective protocols,

so it is difficult to compare our results. However, one research group[12] did provide reliability statistics for two comparable walking protocols using GAITRite technology. The GAITRite walkway is 0.89 × 8.3 m and imbedded with 13,824 sensors that allowed for calculation of temporal and spatial gait parameters. Montero-Odasso et al.[46] reported CVs ranging from 11.02% to 19.27% for outcome variables during DT gait, and Paterson et al.[47] reported CVs ranging from 2.06% to 4.77%. Montero-Odasso et al.'s research involved older adults aged 70+ years, and Paterson et al. involved both young (~20 years) and older adults. This range of ages could explain the differences in CVs reported, as the younger participants may have produced less variability through having more stable gait patterns than older adults.

Koo and Li[43] described relative consistency values as poor (<0.5), moderate (0.5–0.75), good, (0.75–0.9), and excellent (>0.9). In this study, only three variables were below 0.70, indicating that the test–retest reliability using this technology was good to excellent, over these three distances. Montero-Odasso et al.[46] reported ICCs of 0.93 or higher when assessing DT gait, whereas Paterson et al.[47] reported a much larger range of ICCs (0.66–0.94) for the GAITRite technology. Howell et al.[48] and Howell et al.[49] examined the test–retest reliability of a similar DT gait protocol using 3D MOCAP technology with healthy, nonconcussed individuals. Over two testing sessions, Howell et al.[48] reported ICCs ranging from 0.73 to 0.85, whereas Howell et al.[49] evaluated reliability over five testing occasions, and reported ICCs between 0.79 and 0.97. Our measures of relative consistency would appear similar to other technologies that have been used for DT gait.

It was thought that the typical field of data capture (8–10 m) used in most of the studies in this area, might not have been long enough for participants to reach their natural steady-state gait that is, a significant portion of the walking protocol spent in acceleration and deceleration. In this regard, it was expected that the longer 30 m and 1 min out and back protocols would have lower variability than the 12 m protocol. Interestingly this was not the case; all three protocols seem equally consistent in quantifying the gait parameters of interest. This has interesting implications in that the test can be administered in spaces that are relatively confined that is, a clearway of 12 m is all that is needed to perform this gait assessment. It seems that inertial measurement units may be a more reliable technology that would be better suited for dual-task gait assessments outside of a sports laboratory environment, which may be more applicable for safer and quicker return to play for athletes.

4.1 | Limitations and future directions

The sample size may be a limitation to this research; it was very diverse in terms of sporting background, age, and gender, yet still relatively small (n = 20). Given the findings (e.g., a 2 min–12 m gait protocol is reliable), it would be interesting to determine the variability of larger samples and sport-specific cohorts. A larger sample size, particularly comprised of individuals who are involved in

sports with high concussion rates such as rugby and football, could allow for the creation of a more sport-specific normative database that may assist with monitoring concussion recovery and safer return to play. Another possible limitation to these findings is the lack of inter-rater reliability, given that only one researcher administered the DT assessment for all participants. While the testing is very easy to administer from data collection to data download, conducting the same procedures in different environments and/or with varying practitioners is advised as this may influence the resulting reliability of the protocols/technology. Due to the nature of the technology and its software, it was not possible to differentiate the steady-state walking periods with the turns completed which may have some influence on the conclusions reached. Finally, only one cognitive task was used in this research so the effects of other cognitive tasks on the variability of the measures is unknown but would be expected to be minimal.

5 | CONCLUSION

Given the results of this study, in-shoe inertial sensors are a technology that is of high utility and accessibility compared to more traditional technologies for use within DT gait protocols. The absolute consistency across spatiotemporal metrics had no higher variability than 6.5%; the relative consistency was acceptable in 95% of the variables; and the variability across the three protocol distances was similar. Therefore, DT gait tests can be performed in the outdoors or in relatively confined spaces with very little variation in gait parameters. So, the practitioner has a variety of options available to them in terms of testing environment, however, it is still recommended that one protocol is selected and used consistently, rather than using the protocols interchangeably. Future research should expand on these findings within larger sample populations and across individuals within concussion-prevalent sports. Finally, the value of the innersole inertial sensor technology in monitoring concussive gait needs to be investigated.

AUTHOR CONTRIBUTIONS

Courtney Mitchell: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; writing—original draft; writing—review and editing. **John Cronin**: Conceptualization; funding acquisition; investigation; methodology; resources; supervision; writing—original draft; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Individual participant data is not available. The authors confirm that the data supporting the findings of this study are available within the article.

TRANSPARENCY STATEMENT

The lead author Courtney Mitchell affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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