

Using Inertial Foot Pods to Develop a Gait Protocol to Assist with Concussion Diagnosis and
Monitoring

Courtney Jade Mitchell

A dissertation submitted to the Auckland University of Technology in partial fulfilment of the Master
of Sport, Exercise and Health (MSEH)

2022

School of Sport and Recreation

Primary Supervisor: Dr John Cronin

Abstract

Concussions from sports or daily activities of living are an increasingly common mild traumatic brain injury that are frequently undiagnosed or underestimated, therefore there is a need to have valid and reliable protocols that can assess the extent of the concussion and determine readiness for return to activity. With this in mind, the aim of this dissertation was to: 1) review the methods and technologies of dual task (DT) steady state walking protocols with concussed and non-concussed individuals; and, 2) determine the reliability of Plantiga in-shoe inertial sensors with steady state walking paired with a cognitive task. In Chapter 2, the methods and technologies that have been previously utilised to determine concussive influences on gait parameters were critiqued. The primary findings of this literature review were that 3D motion capture (3D MOCAP) and force plates were the most commonly used technologies for analysing concussive gait, with only a few researchers incorporating the use of inertial sensors. A multitude of outcome variables were used to determine differences with concussive and non-concussive gait; gait speed was the sole variable used across all reviewed studies. It was concluded that none of the gait parameters measured by 3D MOCAP and force plates were found to be sensitive enough to consistently determine differences between concussed and non-concussed diagnoses; however, inertial sensors did show some promise. In Chapter 3, a repeated measures experimental design using in-shoe inertial sensors to determine the variability of gait parameters was implemented. This involved non-concussed individuals completing three 2-minute continuous walking protocols (12 m, 30 m, 1 minute out and back) while simultaneously performing a cognitive task of counting backwards in sevens from a randomly generated number between 300 – 500. The primary findings from this study were: 1) the three distances all had similar variability, with acceptable absolute consistency (coefficients of variation < 6.5%; intraclass correlation coefficients > 0.70); 2) the gait variables of interest were reliable across all three protocols; and, 3) inertial sensors appear to be a more affordable, accessible, and easy to use technology as compared to 3D MOCAP and force plates. Given these findings were with a non-concussed population, future research is needed to determine the value of such technology for determining concussion diagnosis via the monitoring of gait parameters using inertial foot pod technology.

Table of Contents

Abstract.....	2
Table of Contents	3
List of Figures.....	4
List of Tables.....	4
Attestation of Authorship.....	5
Co-Authored Works.....	6
Acknowledgements	7
Ethics Approval.....	8
Chapter 1: Introduction and Rationale	9
Chapter 2: Methodological Critique of Concussive and Non-Concussive Dual Task Level Walking Assessments: A Scoping Review	12
Chapter 4: Summary, Practical Recommendations and Future Research Directions.....	57
References	59
Appendices	64
Appendix A – Ethics Approval.....	64
Appendix B - Participant Information Sheet.....	65
Appendix C - Participant Consent Form	69
Appendix D – Literature Review Abstract	70
Appendix E – Reliability Article Abstract.....	71

List of Figures

Figure 1: PRISMA-ScR Flow Diagram of the Study Selection Process.....	14
Table 1: Sample Groups and Protocols.....	17
Table 2: Equipment and Technologies Utilised in Reviewed Studies.....	26
Table 3: Variables and Outcome Measures in Reviewed Articles.....	35
Table 4: Reliability Articles.....	38
Table 5: Descriptive Statistics for 12 m Protocol.....	50
Table 6: Descriptive Statistics for 30 m Protocol.....	52
Table 7: Descriptive Statistics for 1 min Out Protocol.....	53
Table 8: Reliability Statistics for Each Protocol.....	54

List of Tables

Figure 1: PRISMA-ScR Flow Diagram of the Study Selection Process.....	14
Table 1: Sample Groups and Protocols.....	17
Table 2: Equipment and Technologies Utilised in Reviewed Studies.....	26
Table 3: Variables and Outcome Measures in Reviewed Articles.....	35
Table 4: Reliability Articles.....	38
Table 5: Descriptive Statistics for 12 m Protocol.....	50
Table 6: Descriptive Statistics for 30 m Protocol.....	52
Table 7: Descriptive Statistics for 1 min Out Protocol.....	53
Table 8: Reliability Statistics for Each Protocol.....	54

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signature:

Date: 15/11/2022

Co-Authored Works

Candidate Contributions to Co-Authored Papers

Chapter 2 Mitchell, C. J., & Cronin, J. (2023). Methodological Critique of Concussive and Non-Concussive Dual Task Level Walking Assessments: A Scoping Review. <i>International Journal of Environmental Health and Public Health</i> , 20(6), 5227.	Mitchell Cronin	80%, 20%
Chapter 3 Mitchell, C. J., & Cronin, J. B. (2022). <i>The Variability of Dual Task Walking Parameters Using In-Shoe Inertial Sensors in Non-Concussed Individuals</i> [Unpublished manuscript]. School of Sport and Recreation, Auckland University of Technology.	Mitchell Cronin	80%, 20%

Courtney Mitchell

Professor John Cronin

Acknowledgements

Firstly, I would like to thank JC for being my academic supervisor. You have helped me navigate the world of postgraduate studies and I am very appreciative of your constant support. Your passion for learning, people, and diving headfirst into new ideas is inspiring – there's no one else quite like you.

To Paul Winwood, Tracey Clissold, and Sheree Cooper, I am eternally thankful for your ongoing support through my academic journey and in life. I will never be able to show how grateful I am for your presence in my life, whether that is celebrating my achievements or encouraging me through my struggles during this journey. I appreciate you all so much.

A very big thank you to those who participated in my research. Without you, there would be no Master's research for me to conduct. I am very grateful for the time you all provided to help with my data collection. Thank you also to the Auckland University of Technology and the School of Sport and Recreation for the opportunity to carry out this research project. Thank you to AUT for the financial support through the Postgraduate Research Scholarship. Thank you to Barrie Jennings for provision of the Plantiga technology and financial assistance to undertake this research.

I would like to recognise the support from my friends and family who have somehow managed to deal with my fluctuating stress levels during my Master's. Even when you have no idea what I am rambling on about, you all still support and encourage me and let me do my thing. In particular, I would like to acknowledge my parents for always pushing me to do my best and supporting my academic journey. Without your understanding and unconditional support, I would not be able to set myself such high aspirations.

Finally, my partner Sam, thank you for being my number one supporter throughout my whole tertiary journey. The endless love and patience that you have given me, and your willingness to listen to me talk about things that you have no knowledge of or interest in means the world to me. Your ability to calm me down when things got hectic and overwhelming is unparalleled – I genuinely could not have gotten through this without you.

Ethics Approval

The Auckland University of Technology Ethics Committee (AUTEK) approved this research on 15/03/2022. Ethics Application 22/23.

Chapter 1: Introduction and Rationale

1.1. Background

Concussions are a mild traumatic brain injury that individuals can experience through sport that are frequently missed or underestimated resulting in individuals returning to sport earlier than they should; which may 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 event ^(3,4). 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 ⁽⁶⁻¹⁰⁾.

There is an abundance of research that has investigated the efficacy and utility of DT gait assessment in concussion diagnosis ^(6, 7, 9, 11-29). Much of the research in this area has used 3D MOCAP and force plate technology to determine the influence of concussion on gait parameters ^(6, 7, 11-16, 18-24, 26). However, this technology is largely inaccessible to practitioners outside of a well-funded laboratory due to restrictions such as portability, cost of the equipment, and the expertise and time required to process and analyse the data. Thus, the subsequent DT protocols may be limited to usage primarily within research environments, with few opportunities to actively diagnose and monitor concussions sustained in the field.

The advent of technologies such as inertial sensors may enable DT testing outside of the sports laboratory 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 being sensitive to detecting changes in DT gait ^(9, 25, 27, 28, 30). However, the reliability has not been well documented and there may be better placement of sensors than the lumbar and dorsum sites utilised in the research to date, but researchers have provided a starting point for ongoing investigation. For example, it would be interesting to determine if inertial sensors that quantify the foot-ground interaction (e.g., inner sole sensors) offer any diagnostic benefits in this area, thus providing the rationale for completing this dissertation.

1.2. Purpose Statement

The primary intention of this dissertation was to determine the reliability of in-shoe inertial sensors and develop a dual task walking protocol that can be utilised to diagnosis concussion and monitor return to play readiness. This investigation incorporated healthy, uninjured individuals as participants and was completed for the following reasons:

- a) To determine what current technologies and/or outcomes measures have been the most successful in distinguishing between concussed and non-concussed individuals with a dual task walking protocol.
- b) To establish the reliability of insole inertial sensors and develop a reliable dual task walking protocol.

Previously, researchers have utilised many different technologies to develop dual task walking protocols as a means of identifying concussed individuals. The findings of this research could be used to expand on these findings through enhancing clarity of which methodological aspects are key to a reliable walking protocol.

This dissertation attempted to highlight the emergence of new technology that may be better suited to identifying concussion diagnosis and establish the reliability of this technology when used in conjunction with concussion identification.

1.3. Research Aims and Hypothesis

The preliminary aims of this dissertation were to: a) examine the literature and determine what technologies and/or outcome variables were utilised within concussion gait protocols; and, b) examine the literature to determine what technologies were the most reliable in relation to concussive gait. The primary aims of this dissertation were to: a) identify the variables used in previous concussive gait protocols that were sensitive to detect differences in concussed individuals; and, b) understand the reliability of in-shoe inertial sensors in a non-concussed population. If the results were found to be promising in a non-concussed population, then the natural evolution of this research would be with concussed individuals. We hypothesised that the reliability associated with the variables of interest (gait speed and stride length) as measured by the foot pod inertial sensors, would be acceptable. It was also hypothesised that a longer distance walking protocol would yield the least variability in developing a dual task walking protocol.

1.4. Structure of the Dissertation

Chapter 2 of this dissertation is a scoping review of what methods and technologies have been utilised to determine concussive influences on gait parameters. This review outlines which technologies and/or outcome measures were the most sensitive at detecting concussive gait.

Chapter 3 contains the original experimental investigation using in-shoe inertial sensors to determine the variability of gait parameters across three 2-minute continuous walking protocols (12 m, 30 m, 1 minute out and back) while performing a cognitive task of counting backwards in sevens from a randomly generated number between 300 – 500 with non-concussed individuals.

Chapter 4 is the final chapter which serves as the conclusion and summary of the dissertation. Practical recommendations, limitations of the present study and future research opportunities are presented in this chapter.

Chapter 2: Methodological Critique of Concussive and Non-Concussive Dual Task Level Walking Assessments: A Scoping Review

2.1 Preface

The purpose of this chapter was to identify and review the literature relating to the protocols used to determine differences between concussive and non-concussive gait. The topics in this chapter identify the technologies and methods (walking distances, cognitive tasks, variables, etc.) incorporated within each protocol. This review also highlights the utility and affordability of these technologies, with future recommendations provided.

2.2 Introduction

Concussions are a mild traumatic brain injury (mTBI) that individuals can experience through sport that are frequently missed or underestimated resulting in individuals returning to sport earlier than they should, increasing the risk of sustaining a musculoskeletal injury^(1,2) or leading to further brain damage if a second concussion is experienced in close proximity to the first event^(3,4). 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⁽⁶⁻¹⁰⁾.

Protocols incorporating a cognitive task alongside a gait assessment are becoming frequently utilised to evaluate the effects of concussion^(12, 17, 23). The Stroop test, which involves participants responding to an auditory or visual cue whilst undergoing locomotion, requires equipment to facilitate the test and record the accuracy and speed of responses^(6, 19, 20, 22, 23, 26, 31-33). Other more common cognitive dual tasks include reciting the months of the year in reverse order, subtracting by sixes or sevens from a given number, or spelling common five letter words in reverse, while walking along a level walkway^(7, 11-16, 21, 27, 28, 34-37). Gait variables such as walking speed, stride length and cadence are quantified to determine any variability through the introduction of a cognitive task^(12, 13, 17, 27, 38).

To measure the physical variables, 3D motion capture (3D MOCAP) and/or force plates are commonly used to differentiate between concussive diagnoses by assessing postural balance and control^(6, 7, 9, 11-16, 18-21, 31, 34, 35, 37). Inertial measurement units^(8, 27, 28, 30, 38, 39) and accelerometers⁽²²⁾ are other forms of technology that have been used for DT concussion gait analysis. However, whether certain

technologies and/or certain variables are better suited to discriminating between concussed and non-concussed diagnoses is unknown. Of particular interest to the authors and that which provides the purpose of this scoping review was understanding the methodological approaches taken by various research groups and determining those variables that could consistently and reliably differentiate between concussed and non-concussed individuals.

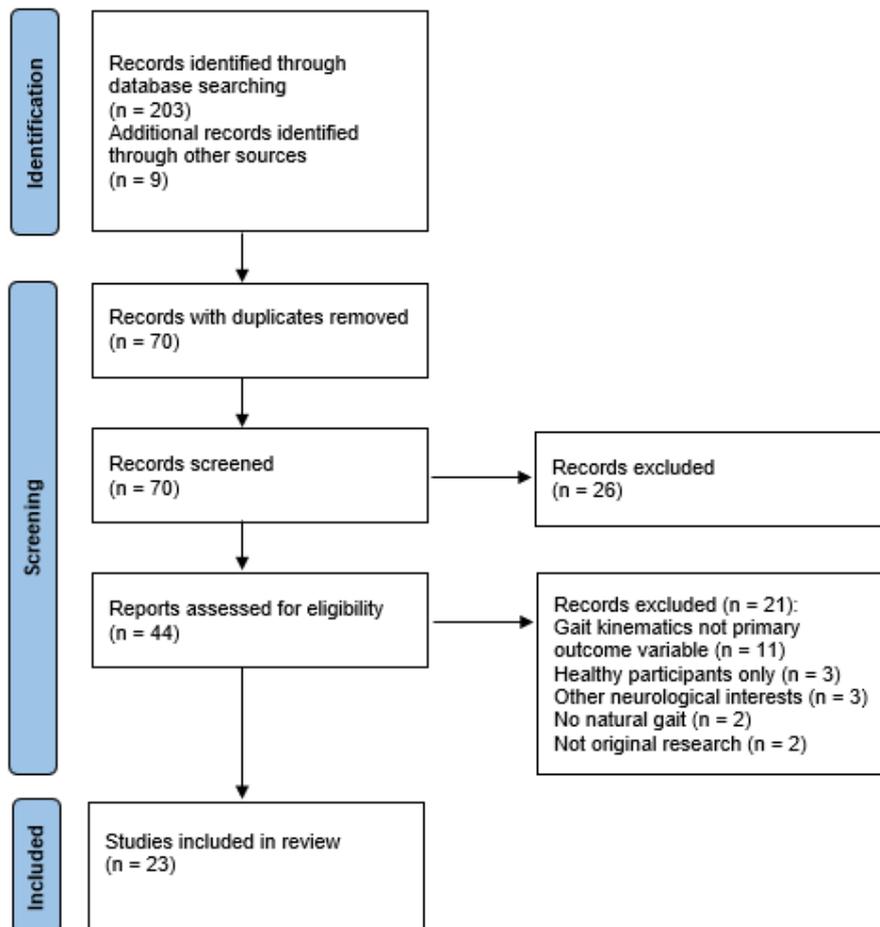
2.3 Methods

2.3.1 Data Sources and Searches

A scoping review was conducted guided by the standards presented by the Preferred Reporting Item for Systematic Reviews and Meta-Analysis extension for Scoping Reviews (PRISMA-ScR) ⁽⁴⁰⁾. This review aimed to examine the methodological approaches, determine those variables that could consistently and reliably differentiate between concussed and non-concussed individuals, identify limitations of current technologies and related protocols and, finally, to outline areas of future research for concussion assessment. MEDLINE via PubMed, CINAHL Complete via EBSCO, EBSCOhost, SPORTDiscus and Scopus databases were searched for relevant articles from the inception of the databases until 31 December 2021. The search strategy included five concepts (concussion, mTBI, cognition, gait and dual task) and a combination of key words to adapt to each database. From the initial screening, 70 articles were identified, and titles and abstracts were screened to determine relevance to review. Forty-four full-text articles were examined to determine inclusion eligibility. Reference lists of included articles were searched for other potentially relevant information. A total of 23 articles were identified as being eligible for full-text review and subsequent analysis (Figure 1).

Figure 1: PRISMA-ScR Flow Diagram of the Study Selection Process.

The flow of information through the review phases is depicted in Figure 1, detailing the number of articles that were included and excluded in the review, with reasons for exclusions.



2.3.2 Study Selection

Studies were included if a steady state DT walking assessment was used; the DT involved a cognitive task paired with a steady state gait task; individuals had a concussion, either through sport or other activity, or mild traumatic brain injury with healthy individuals used as control subjects; and kinematic walking measures were reported. There were no restrictions placed on the age or gender of participants. Articles were excluded if steady-state gait was not the primary dependent variable of cognitive task performance, such as reaction time, tandem gait, balance or gait termination time. Review articles and case studies were excluded. Full-text articles were retrieved and scanned when inclusion could not be determined by screening titles and abstracts. Articles that involved all healthy participants or those with a more severe brain injury were excluded from the analysis. Risk of bias was mitigated in this research, given the focus was more a technological/methodological critique rather than a review of the outcome measures and findings as such.

2.3.3 Data Extraction

One reviewer (C.M.) extracted the data using a customised designed standardised Excel database (version 2201, Microsoft, Redmond, WA, USA) which was validated by a secondary reviewer (J.C.). General study information (i.e., author, year), subject characteristics (i.e., sample size, age, concussion history, sport/activity), type of study (i.e., cross-sectional and prospective), methods of assessment (i.e., testing equipment, environment, protocol) and primary outcome measures (e.g., means and standard deviations of average gait velocity) were extracted. Descriptive information relating to the sport and performance level were used to categorise each of the participants. A wide array of definitions for elite, sub-elite and novice athletes exist⁽³⁷⁾. Therefore, in order to clearly differentiate between groups with concussions, skill level was grouped according to the level at which participants were competing. National or regional representatives were classified as elite athletes. Participants competing at university or collegiate (Uni/Col) were categorised as sub-elite. Recreational athletes were deemed as such (Rec) and those who did not experience a sport-related concussion were classified as NoSport. Adolescent athletes were categorised as high school (HS) athletes.

2.3.4 Role of the Funding Source

This systematic review was funded by Movement Solutions. The funder played no role in the design, collation, synthesis and writing of this review.

2.4 Results

2.4.1 Study Characteristics

Eight of the twenty-three articles (35%) employed prospective designs, with assessments at two to five time points over the course of the study^(6, 7, 12, 15, 16, 22, 38, 41). Fifteen articles (65%) utilised cross-sectional designs^(11, 13, 14, 17, 19-21, 23-30). The total number of participants used across the studies was 1030, with 474 participants categorised as concussed subjects and 556 participants categorised as non-concussed controls. Due to the lack of detail provided, it is unclear as to whether there was any repeated usage of sample groups. Grade II concussion parameters described by the American Academy of Neurology (AAN) were detailed in seven articles^(11-16, 21) and seven articles used the latest Consensus Statement on Concussion in Sport (CsoCiS)^(6, 7, 22, 25, 27, 28, 41). One article used the Veteran Health Affairs/Department of Defence mTBI criteria for concussion diagnosis⁽³⁰⁾ and seven articles did not state the method of concussion diagnosis^(19, 23, 24, 26, 29, 38). Concussions were diagnosed by certified athletic trainers and/or medical professionals in 17 articles^(6, 7, 11, 12, 15-17, 19, 21, 23-25, 27-29, 38, 41); however, the remaining six did not state who diagnosed the concussions of the participants^(13, 14, 20, 22, 26, 30).

2.4.2 Participants

From the 1030 participants, 54% were male and 49% were female; the sex of the participants was not reported in one study⁽¹⁶⁾. There was insufficient detail provided in each of the studies to determine if there was any overlap of sample groups. The age of participants most commonly ranged between 13 and 22, often being high school and university students and athletes. One study involved adults over 64 years of age⁽²⁴⁾. The majority of concussions experienced by participants were sport-related, with the sporting level ranging from elite athletes, intercollegiate athletes, and high school athletes to local and recreational athletes. Three studies included subjects who had sustained a concussion through activities of daily living^(15, 16, 41). Subjects experienced concussion through a variety of sports with the most common sports reported being football, American football and ice hockey ($n = 2$)^(28, 38).

2.4.3 Gait Protocol

The description of the gait protocols can be seen in Table 1. The most common distance covered for the protocols was between 8 and 10 m ($n = 11$)^(11, 12, 14-17, 19, 21, 23, 24, 38). All 23 articles (100%) involved participants walking at a self-selected pace, 14 of which had participants walking barefoot^(6, 7, 11-13, 15, 16, 22, 25, 27, 28, 30, 38, 41). Testing locations were described as a laboratory ($n = 6$)^(12, 13, 17, 19, 23, 26), walkway or hallway ($n = 12$)^(6, 7, 11, 14-16, 22, 24, 28, 29, 38, 41) or were unspecified ($n = 5$)^(20, 21, 25, 27, 30). The most frequent number of trials used across the articles was five trials per testing condition ($n = 9$)^(11, 12, 16, 17, 21, 24-27), followed by between eight and ten trials ($n = 4$)^(6, 7, 19, 41). The amount of practice trials varied from one⁽²²⁾, four^(19, 23) and “several”^(13, 14, 21). In most circumstances (17 articles—74%) it was not stated whether any practice or familiarisation took place. Inter-trial rest periods were described as being 30 s⁽¹⁷⁾ and “several minutes”⁽¹³⁾; however, for the most part (91% of articles) the rest periods were not detailed. Level walking as a single-task (ST) assessment protocol was used in 21 studies^(6, 7, 11-17, 19-21, 23, 24, 26-30, 38, 41); two articles did not include a ST assessment^(22, 25). There was considerable variation in the number of testing occasions for each study: eight articles had one testing occasion up to 72 h^(11, 13, 21), 5–7 days⁽²⁵⁻²⁸⁾ or 4–15 weeks⁽²⁹⁾ post-concussion; three articles included four testing occasions at time points of up to 72 h, 5–7 days, 2 weeks and 1 month post-concussion^(12, 15, 16); five testing occasions were utilized in four articles at time points of up to 72 h, 5–7 days, 2 weeks, 1 month and 2 months post-concussion^(6, 7, 22, 41); one article⁽³⁸⁾ had two testing occasions with the initial occasion up to 21 days post-concussion and the second occasion occurring once no symptoms were being experienced; one article incorporated one testing occasion and did not detail how soon participants were recruited following a concussion being experienced⁽¹⁴⁾; six articles had one testing occasion, where participants had experienced a concussion during their lifetime (“history of concussion”)^(17, 19, 20, 23, 24, 30)

Table 1: Sample Groups and Protocols

Description of the sample groups and assessment protocols in the reviewed articles.

Author (Year)	Sample Size	Age	Concussion Classification	Sport	Protocol Description
Parker et al. (2005) ⁽¹¹⁾	<i>n</i> = 20	C	<i>n</i> = 10, 6 F, 4 M	20.20 ± 1.7 y	ST: walk down a 10 m level walkway at a comfortable self-selected pace while barefoot. DT: spelling five letter words in reverse, subtraction by sevens and reciting months of the year in reverse order. DT randomly selected for each walking trial Testing began with five trials of ST, followed by the DT condition. C referred for testing as soon as possible after injury.
<i>n</i> = 10, 6 F, 4 M	19.90 ± 1.9 y	Concussion Classification:	MP	AAN Grade II	
Uni/Col and Rec					
Parker et al. (2006) ⁽¹²⁾	<i>n</i> = 30	C	<i>n</i> = 15, 6 F, 9 M	20.60 ± 1.6 y	ST: walk down a 10 m level walkway at a comfortable self-selected pace while barefoot. DT: spelling five letter words in reverse, subtraction by sevens and reciting months of the year in reverse order. DT order rotated across trials. Each session began with five trials of ST walking followed by four to five trials of DT. All C were tested within 48 hrs post injury and 5, 14 and 28 days post injury. NC tested at similar intervals. Testing conducted in laboratory.
NC	<i>n</i> = 15, 6 F, 9 M	Concussion Classification:	MP	AAN Grade II	
Uni/Col and Rec					
Catena et al. (2007) ⁽¹⁴⁾	<i>n</i> = 28. University students	C	<i>n</i> = 14, 6 F, 8 M	22.3 ± 4.5 y	ST: walk down an 8 m walkway at a self-selected pace. DT: QA = spelling a common five letter word in reverse; continuous subtraction, reciting months of year in reverse. Order of tasks not shared prior to testing. Several practice trials allowed to ensure familiarity and foot contact was made with both force plates.
NC					

<p>$n = 14, 6 F, 8 M$ $22.3 \pm 3.1 y$ Concussion Classification: AAN Grade II MP Sport not stated.</p>	
<p>Catena et al. (2007) ⁽¹³⁾ $n = 28$ C $n = 14, 6 F, 8 M$ $22.29 \pm 4.5 y$ NC $n = 14, 6 F, 8 M$ $22.29 \pm 3.1 y$ Concussion Classification: AAN Grade II Who diagnosed not stated Sport not stated</p>	<p>No ST; walking component of DT: walk down an 8 m walkway at a comfortable self-selected pace while barefoot. DT 1: QA = spelling a common five letter word in reverse, continuous subtraction by a certain number and reciting the months of the year in reverse order. Several practice trials, ensuring whole foot contact made with force plate. Each participant performed approx. 60 trials. Each trial lasted approx. 8 s. Returned to same starting position for each trial. Several minutes rest twice during the testing session during transition to new testing condition. C testing occurred within 48 h post injury. Testing completed in laboratory.</p>
<p>Parker et al. (2007) ⁽¹⁵⁾ $n = 58$ C $n = 29, 14 F, 15 M$ $21.60 \pm 3.3 y$ NC $n = 29, 14 F, 15 M$ $21.38 \pm 3.4 y$ Concussion Classification: AAN Grade II MP Uni/Col and ADL</p>	<p>ST: walk down a 10 m level walkway at a comfortable self-selected pace while barefoot. DT: spelling five letter words in reverse, subtraction by sevens and reciting months of the year in reverse order Order of individual tasks rotated across trials. C tested within 48 h post injury, and at 5, 14 and 28 days post injury. NC tested at same intervals.</p>
<p>Parker et al. (2008) ⁽¹⁶⁾ $n = 56$ C athletes $n = 14$ $20.71 \pm 1.3 y$ C non-athletes $n = 14$ $22.43 \pm 4.6 y$</p>	<p>ST: walk down a 10 m level walkway at a self-selected pace while barefoot. DT: spelling five letter words backwards, subtraction by sevens and reciting the months of the year in reverse. Order of individual tasks rotated across trials. Each testing session began with four to five trials of ST walking followed by four to five trials of DT. C tested within 48 h post injury, and at 5, 14 and 28 days post injury. NC tested at same time intervals.</p>

NC athletes <i>n</i> = 14 20.64 ± 1.5 y NC non athletes <i>n</i> = 14 22.93 ± 4.3 y Concussion Classification: AAN Grade II MP Uni/Col, Rec, and NoSport	
Martini et al. (2011) ⁽¹⁷⁾ <i>n</i> = 68 C <i>n</i> = 28, 11 F, 17 M 21.00 y NC <i>n</i> = 40, 20 F, 20 M 21.72 y Concussion Classification: MP and self-reported Sport not stated	ST: walking along GAITRite walkway (0.89 × 8.3 m) at a self-selected pace. DT: Brooks' Spatial Memory Task—verbally recite the spatial location of digits 1 through 8 in an imaginary 4 × 4 grid. Participants recall position of numbers while walking. 24 unique grids presented randomly. Conditions: ST walk, DT walk. Each condition ×5, in a random order. 30 s rest between trials Tested in research laboratory.
Fait et al. (2013) ⁽¹⁹⁾ <i>n</i> = 12 C <i>n</i> = 6, 2 F, 4 M 19.7 ± 2.3 y NC <i>n</i> = 6, 2 F, 4 M 20.1 ± 2.7 y Concussion Classification: MP How diagnosed not stated Elite athletes	ST: straight unobstructed walk 8.75 m at a comfortable walking pace without stopping. DT: modified visual Stroop Four level walking trials conducted first to establish walking speed. A baseline for the Stroop word task was performed (two 5 s trials). Overall, two gait conditions combining the different walking Stroop (with or without) tasks. Five trials of each condition performed in a random order Testing conducted in laboratory
Howell et al. (2013) ⁽⁶⁾ <i>n</i> = 40 C <i>n</i> = 20, 2 F, 18 M 15.3 ± 1.3 y	ST: walk at a self-selected pace while barefoot, along a walkway. DT: auditory Stroop test Eight to ten consecutive trials completed for each ST and DT conditions. C tested within 72 h of sustaining concussion, then 1 week, 2 weeks, 1 month and 2 months post injury. NC tested similar schedule.

NC

n = 20, 2 F, 18 M

15.6 ± 1.0 y

Concussion Classification:

CsoCiS

MP

HS athletes

Cossette et al. (2014) ⁽²⁰⁾

n = 14

C

n = 7, 6 F, 1 M

20.0 ± 1.6 y

NC

n = 7, 6 F, 1 M

22.4 ± 1.4 y

Concussion Classification:

Not stated

Rec

Howell et al. (2014) ⁽⁷⁾

n = 46

C

n = 23, 3 F, 20 M

15.4 ± 1.3 y

NC

n = 23, 3 F, 20 M

15.7 ± 1.3 y

Concussion Classification:

CsoCiS

MP

Sport not stated

Chen et al. (2015) ⁽²¹⁾

n = 60

C

n = 15, 6 F, 9 M

21.3 ± 3.3 yrs

NC

n = 15, 6 F, 9 M

21.2 ± 3.4 yrs

ST: Walking 6 m at a comfortable and constant speed.

DT:

- Visual Stroop

- Verbal fluency (naming as many words beginning by a given letter)

- Arithmetic (counting backward by two from a given number).

Four baseline trials initially (level walking no cognitive task); then every combination of conditions repeated four times. Elements of cognitive tasks were changed across trials.

ST: walk barefoot at a self-selected pace along a walkway.

DT 1: single auditory Stroop

DT 2: multiple auditory Stroop = four responses

DT 3: QA = spelling a five letter word backwards, subtracting by 6s or 7s or reciting months in reverse order.

QA randomly selected for each trial.

Eight to ten trials of each ST and DT conditions.

C tested within 72 h of injury, and again at 1 week, 2 weeks, 1 month and 2 months post injury. NC tested at similar timeline.

ST: 8 m walk at a self-selected pace.

DT: spelling five letter words in reverse, subtraction by sevens and reciting months of year in reverse order.

Randomly selected for each trial

Several practice trials for participant familiarity

Data from five trials collected for each testing condition

C referred for testing within 48 h of injury

Concussion Classification:

AAN Grade II

MP

Sport not stated

Howell et al. (2015) ⁽²²⁾

n = 17

C

n = 10, 3 F, 7 M

19.0 ± 5.5 y

NC

n = 7, 4 F, 3 M

20.0 ± 4.5 y

Concussion Classification:

CSoCiS

Who diagnosed not stated

Sport not stated

Cossette et al. (2016) ⁽²³⁾

n = 27

C

n = 14, 6 F, 8 M

13.0 ± 1.6 y

NC

n = 13, 5 F, 8 M

12.8 ± 1.6 y

Concussion Classification:

MP

Sport not stated

Martini et al. (2016) ⁽²⁴⁾

n = 77

20 years old

C

n = 16, 7 F, 9 M

20 ± 2 y

NC

n = 24, 12 F, 12 M

22 ± 2 y

40 years old

C

No separate ST: barefoot walk at a self-selected pace along a walkway

DT: auditory Stroop test.

Practice trial first.

C tested within 72 h post injury, then 1 week, 2 weeks, 1 month and 2 months post injury. NC tested at similar schedule.

No separate ST: walk 8 m at a comfortable pace

DT:

- Visual Stroop test

- Verbal fluency of naming words, beginning with a given letter

- Counting backward by twos from a given number

Each session began with four trials of level walking to familiarise participants with the lab. All combinations of locomotor and cognitive tasks were repeated four times.

ST: walk along a 10 m walkway at a self-selected pace.

DT: Brooks' Mental Task—remember and recall the order and location of eight sequential numbers in a 4 × 4 grid that were presented via an audio recording.

Five trials of four walking conditions.

$n = 4, 1 \text{ F}, 3 \text{ M}$

$47 \pm 4 \text{ y}$

NC

$n = 15, 8 \text{ F}, 7 \text{ M}$

$45 \pm 4 \text{ y}$

60 years old

C

$n = 7, 1 \text{ F}, 6 \text{ M}$

$63 \pm 4 \text{ y}$

NC

$n = 11, 4 \text{ F}, 7 \text{ M}$

$64 \pm 4 \text{ y}$

Concussion Classification:

MP, self-reported

Sport not stated

Berkner et al. (2017) ⁽³⁸⁾

$n = 81$

C

$n = 37, 20 \text{ F}, 17 \text{ M}$

$16.2 \pm 3.1 \text{ y}$

NC

$n = 44, 25 \text{ F}, 19 \text{ M}$

$15.0 \pm 2.0 \text{ y}$

Concussion Classification:

MP

HS/Rec

Yasen et al. (2017) ⁽⁴¹⁾

$n = 40$

C

$n = 20, 10 \text{ F}, 10 \text{ M}$

$21.2 \pm 4.4 \text{ y}$

NC

$n = 20, 10 \text{ F}, 10 \text{ M}$

$21.4 \pm 4.6 \text{ y}$

Concussion Classification:

CSoCiS

MP

Rec/ADL

ST: barefoot level walking at a self-selected pace 8 m to a marker and return to start

DT: spelling a five letter word backwards, subtracting 6 s or 7 s from a random 2 digit number or reciting months in reverse from a random month. DT was randomly selected for each trial.

C tested at two periods: 1st within 21 days of injury, 2nd after no longer experiencing concussion symptoms. NC only tested once.

ST: barefoot walking at a self-selected pace along a walkway.

DT: auditory Stroop task identifying the pitch of words “high” or “low” spoken in either a high or low pitch.

Eight to ten trials completed at each session.

Tested at points within 72 h post-concussion, then again at 1 week, 2 weeks, 1 month and 2 months post-concussion. NC tested at similar periods.

<p>Howell et al. (2018) ⁽²⁵⁾ <i>n</i> = 59 C <i>n</i> = 18, 9 F, 9 M 19.9 ± 1.2 y NC <i>n</i> = 41, 12 F, 29 M 19.0 ± 0.9 y Concussion Classification: CSoCiS MP Uni/Col</p>	<p>No separate ST: walking barefoot at a self-selected pace towards a target placed 10 m away, walk around it and return to start position. DT: spelling a five letter word in reverse, subtracting by 6 s or 7 s from a 2 digit number or reverse month recitation. Five trials completed. C tested within 5 days post injury. NC tested as part of baseline testing in preseason.</p>
<p>Solomito et al. (2018) ⁽²⁶⁾ <i>n</i> = 31 C <i>n</i> = 16, 7 F, 9 M 14.6 ± 1.8 y NC <i>n</i> = 15, 6 F, 9 M 13.8 ± 1.4 y Concussion Classification: Not stated Sport not stated</p>	<p>ST: walking at typical pace in a laboratory. DT 1: recite months of the year or days of the week in reverse. DT 2: auditory Stroop test. Cognitive load trials were performed following ST. A minimum of five strides of data were collected per side for each of the three testing conditions. C tested within one week of receiving medical clearance</p>
<p>Howell et al. (2019) ⁽²⁸⁾ <i>n</i> = 114 C <i>n</i> = 49, 24 F, 25 M 14.9 ± 1.9 y NC <i>n</i> = 65, 31 F, 34 M 14.9 ± 1.6 y Concussion Classification: CSoCiS MP HS sport</p>	<p>ST: walk at a self-selected pace to a target placed 8 m in front, walk around, return to start. DT: walking and cognitive. Cognitive: spelling five letter word in reverse, subtracting in 6 s or 7 s from a random two digit number or reciting months of the year in reverse. Randomly chosen. Testing in a quiet hallway, barefoot.</p>
<p>Howell et al. (2019) ⁽²⁷⁾ <i>n</i> = 124 C</p>	<p>ST: walking barefoot at a self-selected pace, to a target 8 m away, around it, and back to start position. DT: spelling five letter word in reverse, subtracting in 6 s or 7 s from a two digit number, or reverse month recitation. DT test rotated between trials to minimise learning effects.</p>

<p>$n = 54$, 25 F, 29 M 20.3 ± 1.1 y NC $n = 60$, 22 F, 38 M 18.9 ± 0.7 y Concussion Classification: CSoCiS MP Uni/Col</p>	<p>Five trials completed in each condition, mean from five trials used for analysis. C tested within 5 days of injury. NC tested as part of preseason testing.</p>
<p>Gagne et al. (2021) ⁽²⁹⁾ $n = 40$ C $n = 20$, 10 F, 10 M 22.1 ± 3.0 y NC $n = 20$, 10 F, 10 M 22.55 ± 2.7 y Concussion Classification: MP Sport not stated</p>	<p>ST: walk back and forth 10 m for a total of 40 m at a natural and comfortable pace. DT: counting backwards in 7 s, producing different words beginning with a specific letter. Instructed to perform the cognitive task as fast and accurately as possible. Tested in a corridor in the rehab institute</p>
<p>Martini et al. (2021) ⁽³⁰⁾ $n = 122$ C $n = 65$, 45 F, 20 M 39.6 ± 11.7 y NC $n = 57$, 36 F, 21 M 36.9 ± 12.2 y Concussion Classification: Veteran Health Affairs Historic Concussion</p>	<p>ST: walking at a comfortable, self-selected pace, eight laps of 13 m path with 180 degree turns at each end. DT: auditory Stroop task identifying the pitch of words “high” or “low” spoken in either a high or low pitch.</p>

Key: n, number of participants; C, concussed subjects; NC, non-concussed subjects; F, female; M, male; y, years; MP, Medical professional; CSoCiS, Current Statement of Concussion in Sport; AAN, American Association of Neurology; HS, high school athletes; Uni/Col, university/colle giate athletes; Rec, recreational athletes; ADL, activities of daily living; ST, single task; DT, dual task; QA, question and answer; m, metres; h, hours.

2.4.4 Cognitive Task

Eight different cognitive tasks were utilised in the DT gait protocols across the 23 studies (see Table 1). These included: spelling a common five letter word backwards; subtracting by sixes and/or sevens; reciting the months of the year in reverse; auditory Stroop; visual Stroop; and Brooks' spatial memory task, verbal fluency, and arithmetic. The most commonly used DT cognitive tasks ($n = 14$) were spelling common five letter words backwards, subtracting by sixes and/or sevens and reciting the months of the year in reverse (6, 11-16, 20, 21, 25-29, 38). An auditory Stroop assessment was the next most common cognitive task ($n = 6$) (6, 7, 22, 26, 30, 41), followed by a visual Stroop test (19, 20, 23) and a verbal fluency task (20, 23, 29) (both $n = 3$). All 23 studies included at least one DT assessment. In terms of the number of cognitive tasks used within each methodology, a single DT assessment was used in seven articles (6, 17, 19, 22, 24, 30, 41), two different DT tests were used in two articles (26, 29), three different cognitive tasks were used in six articles (7, 12, 15, 16, 20, 23) and eight articles randomised participants' single DT trial from three DT options (11, 13, 14, 21, 25, 27, 28, 38).

2.4.5 Equipment

The equipment used in the articles reviewed can be observed in Table 2. Motion capture (3D MOCAP) was used in 16 articles (6, 7, 11-16, 19-24, 26, 41). The number of markers placed on bony landmarks mostly ranged between 25 and 32 ($n = 12$) (6, 7, 11-16, 21, 22, 24, 41), with one group of researchers utilising 16 markers (26) and three research groups using four markers (19, 20, 23). The number of cameras used ranged between six and ten ($n = 12$) (6, 7, 11-16, 20-22, 41); however, four research groups did not state how many cameras were used (19, 23, 24, 26). The most widely used sampling rate was 60 Hz ($n = 10$) (6, 7, 11-14, 16, 21, 22, 41), where other researchers sampled data at 100 Hz (19), 120 Hz (26) and 240 Hz (24). The sampling rate was not stated in three papers (15, 20, 23). Marker trajectory data was filtered using a low-pass fourth order Butterworth filter by 11 research groups (69%), with a cut-off filter of 6 Hz (19, 23) and 8 Hz (6, 7, 11-14, 16, 20, 21, 41) being the most common cut off frequencies. The method of data filtering was not stated in five articles (15, 20, 22, 24, 26).

Table 2: Equipment and Technologies Utilised in Reviewed Studies.

Description of the equipment and technologies utilised and methods of calculating variables in the reviewed articles.

Author (Year)	Equipment	Variables and Method of Calculation	Testing Protocol Reliability
Parker et al. (2005) (11)	<p>Six camera motion capture ExpertVision HIRES system (Motion Analysis Corporation, Santa Rosa, CA, USA). Twenty-five reflective markers on bony landmarks. Marker trajectory data collected at 60 Hz; low-pass filtered using a fourth-order Butterworth filter, cut off frequency 8 Hz. Motion analysis system calibrated before each session (volume = 4 m long, 1.5 m wide, 2 m high) Two force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) in series along gait path, sampled at 960 Hz.</p>	<p>Whole body COM position data calculated as the weighted sum of each body segment (13 segments). COM velocities and accelerations estimated using generalised cross-validated spline algorithm. Motion data analysed from heel strike of the trailing limb as it struck the first force plate to the next heel strike of that same limb. EVa software: estimating virtual marker positions to represent internal segment endpoints from the external markers and the relative positions of segmental COM (Motion Analysis Corporation). External markers and estimated joint centres used to calculate the three-dimensional motion for individual body segments and locations of the segmental COM. OrthoTrak 4.0 (Motion Analysis Corporation) used in the calculation of temporal-distance parameters (gait velocity, stride length, stride time and step width).</p>	None
Parker et al. (2006) (12)	<p>Six camera motion capture ExpertVision HIRES system (Motion Analysis Corporation, Santa Rosa, CA, USA) Twenty-five reflective markers on bony landmarks. Marker trajectory data collected at 60 Hz; low-pass filtered using a fourth-order Butterworth filter, cut off frequency 8 Hz. Motion analysis system calibrated before each session (volume = 4 m long, 1.5 m wide, 2 m high).</p>	<p>Whole body COM position data calculated as the weighted sum of each body segment (13 segments) COM velocities and accelerations estimated using generalized cross-validated spline algorithm. Motion data analysed from heel strike of the limb as it struck the first force plate to the next heel strike of that same limb. EVa software: estimating virtual marker positions to represent internal segment endpoints from the external markers and the relative positions of the segmental COM (Version 6.0, Motion Analysis Corporation). External markers and estimated joint centres used to calculate the three-dimensional motion for individual body segments and locations of segmental COM.</p>	None

	<p>Two force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) in series along gait path, sampled at 960 Hz.</p> <p>Data averaged across trials for each task condition (ST and DT)</p>	<p>OrthoTrak 4.0 (Motion Analysis Corporation) used in the calculation of temporal–distance parameters (gait velocity, stride length, stride time and step width).</p>	
<p>Catena et al. (2007) (14)</p>	<p>Eight camera motion capture (Motion Analysis Corporation, Santa Rosa, CA, USA).</p> <p>Twenty-nine retroreflective markers bilaterally on bony landmarks. Marker trajectories sampled at 60 Hz for 4 s; filtered through a low-pass, fourth-order Butterworth filter, cut off frequency 8 Hz.</p> <p>Two sequential force plates (Advanced Mechanical Technologies Inc., Watertown, MA, USA) separated by 25.9 cm in centre of walkway; sampled at 960 Hz for 4 s.</p>	<p>Virtual markers created at joint centres and combined with anthropometric data to determine COM location for each of 13 body segments.</p> <p>Motion data calculated for one complete stride; heel strike on to the first force plate to heel strike of the same foot on the second force plate.</p> <p>Whole body COM calculated from each segment COM using a weighted sum method</p> <p>Velocities calculated using Woltring’s generalised cross-validated spline algorithm.</p> <p>Gait velocity: position change of the body COM and time change during a complete stride.</p> <p>Stride length and stride time: position change of the heel marker and respective time change.</p> <p>Step width: left to right ankle joint centres at heel strike.</p>	<p>None</p>
<p>Catena et al. (2007) (13)</p>	<p>Eight Eagle digital cameras positioned surrounding an 8 m walkway (Motion Analysis Corporation, Santa Rosa, CA, USA)</p> <p>Twenty-nine retroreflective markers on anatomical landmarks</p> <p>EVaRT 4.37A collected data at 60 Hz for 4 s; trajectories filtered with a low-pass fourth order Butterworth filter, cut off frequency 8 Hz.</p> <p>Two in-series strain gauge force plates (Advanced Mechanical Technologies Inc. Watertown, MA, USA), in centre of walkway, flush with floor. Data collected at 960 Hz for 4 s.</p>	<p>COM calculated from 13 different segments.</p> <p>COM calculations based on Dempster’s (Winter 1990) anthropometric data. A weighted sum method used to calculate whole body COM from each segment COM during each time point. COM truncated from first heel strike on to the first force plate to the heel strike of the same foot after the second force plate.</p> <p>COM velocities estimated with Woltring’s generalised cross-validated spline algorithm.</p> <p>COP data calculated for all time points that the subject was in contact with a force plate</p> <p>COM data synchronized with the COP data to find the maximum horizontal separation distance between the COM and COP in sagittal and coronal planes.</p> <p>First five responses recorded so that “starting position and gait velocity did not factor into the number of answer attempts”</p>	<p>None</p>

	<p>Photocell (RadioShack, Fort Worth Tx, USA) and radio telemetry receiver (TS0611T, Isaacs & Associates Inc., Walla Walla, WA, USA) collected at 960 Hz for 4 s.</p>		
Parker et al. (2007) ⁽¹⁵⁾	<p>Eight camera motion capture (Motion Analysis Corporation, Santa Rosa, CA, USA) Thirty-one reflective markers on bony landmarks. Two force plates (Advanced Mechanical Technology, Watertown, MA, USA) positioned in series along gait path.</p>	<p>EVaRT software (Motion Analysis Corporation: Virtual marker positions estimated to represent joint centres and positions of the segmental COM from the external markers. Whole-body COM position calculated as weighted sum of each body segment (13 segments). COM velocities estimated using the generalised cross-validated spline algorithm. One gait cycle: heel strike on the force plate to the next heel strike of the same limb.</p>	None
Parker et al. (2008) ⁽¹⁶⁾	<p>Eight camera motion capture (Motion Analysis Corporation, Santa Rosa, CA, USA) Thirty-one reflective markers on bony landmarks. Marker trajectory data collected at 60 Hz; low-pass filtered using a fourth-order Butterworth filter, cut off frequency 8 Hz. Calibrated prior to each session (volume = 4 m long, 1.5 m wide, 2 m high). Two force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) used in series and sampled at 960 Hz.</p>	<p>Whole body COM position data calculated as the weighted sum of each body segment (13 segments). COM velocities and accelerations estimated using the generalized cross-validated spline algorithm. EVaRT software (Version 4.4, Motion Analysis Corporation): estimating virtual marker positions to represent internal segment endpoints from the external markers, and the relative positions of the segmental centre of mass. One gait cycle: heel strike on the force plate to the next heel strike of the same limb. Data averaged across trials for each task condition (single and dual).</p>	None
Martini et al. (2011) ⁽¹⁷⁾	<p>GAITRite walkway and software 0.89x8.3 m with 13824 sensors embedded recording footfall pressure at 80 Hz.</p>	<p>Normalised velocity: velocity/average leg length Step length: heel centre from step to next step. Stride width: distance of foot from midline over two steps. Double support (%): percent of time in gait cycle where both feet on ground. Averaged data from five trials used for analysis.</p>	GAITRite walkway reliability

	Average performance from five trials for each variable within each condition used for data analysis.		
Fait et al. (2013) ⁽¹⁹⁾	<p>Motion analysis system (Optotrak 3020; NDI, Waterloo, Ontario, Canada), reflective markers fixed on feet, trunk and head.</p> <p>Data sampled at 100 Hz; low-pass filtered at 6 Hz with a fourth-order zero-lag Butterworth filter.</p> <p>Verbal responses recorded (1000 Hz) with a microphone fixed onto headphones worn by the subject. Pink noise (at 80 dB) played into the headphones to minimise distraction from ambient sounds. Trials videotaped to allow examination of responses to the Stroop word task.</p>	<p>Segment COM estimated by digitising the toe of the shoe, the heads of fifth metatarsal bones, the heels of the shoe, the sternal notch, the lateral surface of the humeral heads, and the ears.</p> <p>Individual scores calculated separately for each dependent variable. For each of the gait conditions, individual averaged scores were means across the five trials. The individual overall pooled scores were means of all gait conditions for each athlete.</p>	None
Howell et al. (2013) ⁽⁶⁾	<p>Ten camera motion capture (Motion Analysis Corporation, Santa Rosa, CA, USA)</p> <p>Twenty-nine retroreflective markers on bony landmarks.</p> <p>Data collected at a sampling rate of 60 Hz; marker trajectory data low-pass filtered using a fourth-order Butterworth filter, cut off frequency 8 Hz.</p> <p>Gait events detected from GRFs collected at 960 Hz using three force plates (Advanced Mechanical Technologies, Watertown, MA, USA). Participants verbally responded to the Stroop test using a headset wireless system with microphone (AKG Acoustics, Northridge, CA, USA).</p>	<p>External markers and estimated joint centres used to calculate COM position for each individual body segment.</p> <p>Whole body COM calculated as the weighted sum of all body segments (13 segments).</p> <p>One gait cycle: heel strike to heel strike of the same limb.</p> <p>Average walking speed: mean forward velocity throughout the gait cycle.</p> <p>Step length and step width: distances between right and left heel markers at each heel strike in the AP and ML, respectively.</p> <p>Linear COM velocity: cross-validated spline algorithm from the COM position.</p> <p>Mean of each block of trials for all variables calculated.</p>	None

	For each trial, data were analysed for one gait cycle.		
Cossette et al. (2014) ⁽²⁰⁾	Nine camera motion analysis system (Vicon, CO, USA) recording at 100 Hz. Four triads of reflecting markers placed on subjects' feet, trunk and head.	Average speed over several strides of the targeted walkway.	None
Howell et al. (2014) ⁽⁷⁾	Ten camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA). Twenty-nine retroreflective markers on bony landmarks. Sampled at 60 Hz; marker trajectory data low-pass filtered using a fourth-order Butterworth filter, cut off frequency 8 Hz. Gait events detected from GRF collected at 960 Hz from three force plates (Advanced Mechanical Technologies Inc., Watertown, MA, USA). Verbal responses recorded using a headset wireless system with a microphone (AKG Acoustics, Northridge, CA, USA).	External markers and estimated joint centres used to calculate COM of each individual body segment. Whole body COM position data then calculated as the weighted sum of all body segments. Linear COM velocity calculated using the cross-validated spline algorithm. Average walking speed calculated as mean forward velocity during gait cycle. Gait cycle: heel strike to heel strike of the same limb. Mean of eight to ten trials for each subject calculated for each variable. Data analysed for one gait cycle.	None
Chen et al. (2015) ⁽²¹⁾	Eight camera motion capture (Motion Analysis Corporation, Santa Rosa, CA, USA). 25 retroreflective markers on bony landmarks. Data collected at 60 Hz; marker trajectory data low-pass-filtered using a fourth-order Butterworth filter with the cut off frequency set at 8 Hz. OrthoTrak software (Motion Analysis Corporation) calculated joint angles and gait temporal-distance variables.	Joint angles in sagittal: angular velocities estimated for each joint using the generalized cross-validation spline algorithm. Angular displacements and velocities normalised: phase plots. Data from five trials collected for each testing condition.	None

Howell et al. (2015) ⁽²²⁾	<p>Ten camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA) at a sampling rate of 60 Hz.</p> <p>Retroreflective markers on bony landmarks.</p> <p>Accelerometer (Opal Sensor, APDM Inc., Portland, OR, USA) attached with an elastic belt at L5.</p> <p>Data sampled at 128 Hz.</p>	<p>Linear acceleration measured along three orthogonal axes, x oriented vertically downward, y to the right, z towards the front.</p> <p>Gait velocity: mean forward velocity of the sacral marker during a gait cycle.</p> <p>Heel strikes used to identify the beginning and the end of the gait cycle.</p> <p>Four trials per subject per testing time point.</p>	None
Cossette et al. (2016) ⁽²³⁾	<p>Motion analysis system (Vicon, CO, USA), 100 Hz, used with four triads of reflective markers placed on head, trunk and feet.</p> <p>Low-pass filtered (6 Hz) with a zero lag Butterworth filter.</p>	<p>Specific anatomical references digitized in order to estimate COM positions for the trunk and toe and heel positions for the feet.</p> <p>Gait speed calculated from forward trunk COM movement.</p>	None
Martini et al. (2016) ⁽²⁴⁾	<p>Spatiotemporal and toe clearance data collected using Vicon (CO, USA) system sampling at 240 Hz.</p> <p>Thirty-two reflective markers on bony landmarks.</p>	<p>Gait velocity normalised to height (stature (m)).</p> <p>Step length normalised to height (m).</p>	None
Berkner et al. (2017) ⁽³⁸⁾	<p>Three inertial sensors (Opal Sensor, APDM Inc, Portland, OR, USA) attached to lumbar spine at lumbosacral junction, and dorsum of each foot with an elastic strap.</p> <p>Data obtained at sampling frequency of 128 Hz.</p>	<p>Gait outcome measures (average gait speed, cadence, stride length, double support time) were calculated using Mobility Lab software (Version 2.0; APDM Inc).</p>	None
Yasen et al. (2017) ⁽⁴¹⁾	<p>Ten camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA).</p> <p>Twenty-nine retroreflective markers on bony landmarks.</p> <p>Sampled at 60 Hz; marker trajectory data low-pass filtered using a fourth-order</p>	<p>External markers and estimated joint centres were used to calculate the centre of mass (COM) of each individual body segment. Whole-body COM position data were then calculated as the weighted sum of all body segments (13 segments).</p> <p>Average walking speed was calculated as the mean forward COM velocity throughout the gait cycle.</p>	None

	<p>Butterworth filter, cut off frequency 8 Hz.</p> <p>Gait events were detected from ground reaction forces collected at 960 Hz using three force plates (Advanced Mechanical Technologies, Watertown, MA, USA).</p>		
Howell et al. (2018) ⁽²⁵⁾	<p>Three inertial sensors (Opal Sensor, APDM Inc., Portland, OR, USA) attached to lumbar spine at lumbosacral junction, and dorsum of each foot with an elastic belt.</p> <p>Data obtained at sampling frequency of 128 Hz.</p>	<p>Gait characteristics calculated using Mobility Lab software (APDM Inc.) (average gait speed, cadence, stride length).</p> <p>Average gait speed: combination of cadence and stride length.</p>	None
Solomito et al. (2018) ⁽²⁶⁾	<p>Motion data collected at 120 Hz with Vicon motion analysis system (Vicon Motion Systems, Oxford, UK).</p> <p>Sixteen retroreflective markers on bony landmarks.</p> <p>Vicon Nexus used to calculate all temporal and stride parameters.</p> <p>Data filtered using Woltring filter routine found in the Nexus pipeline.</p> <p>Matlab (Mathworks, Natick, MA, USA) used to calculate COM for each stride.</p>	<p>COM calculated by determining the centre point of the upper thoracic plane (C7 and right and left clavicle markers) and the pelvic plane (sacrum and right and left anterior superior iliac spines).</p> <p>COM displacement measured for a total five strides per task, then averaged.</p> <p>COM velocity: time rate of change of displacement determined for each stride and then averaged over the five strides to obtain a single COM velocity value for each task per study participant.</p>	None
Howell et al. (2019) ⁽²⁸⁾	<p>Opal Sensors (APDM Inc., Portland, OR, USA) attached to lumbosacral junction and dorsum of both feet with elastic strap. Data obtained at sampling frequency of 128 Hz.</p>	<p>Mobility Lab software (ADPM Inc.) calculated gait measures.</p>	None
Howell et al. (2019) ⁽²⁷⁾	<p>Three inertial measurement sensors (Opal Sensor, APDM Inc., Portland, OR, USA) attached at lumbosacral junction and each dorsum of feet. Sampled at 128 Hz.</p>	<p>Gait variables (average gait speed (m/s), cadence (steps/min), stride length (m)) calculated with Mobility Lab software (ADPM Inc.).</p>	None

Gagne et al. (2021) (29)	Stopwatch	<p>Gait speed estimated as total travelled distance (40 m) divided by total time (seconds) as measured with the stopwatch.</p> <p>DTC for gait speed: % difference between average gait speed during the dual-task and the single-task conditions for the same locomotor task, divided by average single-task gait speed for that same locomotor task. DTC calculated for this variable by subtracting baseline ratio of dual-task ratio, divided by baseline ratio $\times 100$.</p>	None
Martini et al. (2021) (30)	Five inertial sensors (Opal Sensors, APDM Inc., Portland, OR, USA)	<p>Comprehensive gait measures were divided into four domains: pace, rhythm, variability and turning. Domain scores were calculated by averaging the Z-scores for each gait variable. Z-scores were multiplied by -1 to reverse scaling, if needed, for consistent sign in domain score calculations.</p>	43, 44

Nine research groups utilised force plates in conjunction with 3D MOCAP^(6, 7, 11-16, 41); two in-series force plates were used in six articles⁽¹¹⁻¹⁶⁾ and three articles used three in-series force plates^(6, 7, 41). A sampling rate of 960 Hz was used in all but two articles^(6, 7, 11-14, 16, 41), with the sampling rate not being specified in these studies^(15, 26).

Inertial measurement units (IMU) were utilised by five research groups^(25, 27, 28, 30, 38). IMUs were placed on the lumbosacral junction and dorsum of each foot ($n = 4$) and recorded data at a sampling rate of 128 Hz^(25, 27, 28, 38). One article placed IMUs on the dorsum of each foot, forehead, lumbar spine and sternum, with the sampling rate not being specified⁽³⁰⁾. A single research group utilised an accelerometer in combination with 3D MOCAP⁽²²⁾. The accelerometer was attached at the L5 vertebrae and collected data at a sampling rate of 128 Hz.

Three articles used a microphone to record participants' responses during their respective DT^(6, 7, 19). A GAITRite walkway, sampling at 80 Hz, was used to collect gait data in one article⁽¹⁷⁾. One article utilised a manual stopwatch to time participants' gait⁽²⁹⁾.

2.4.6 Outcome Measures

The outcome measures of interest are detailed in Table 3. Gait velocity was the most studied measure in terms of identifying concussive gait impairments. No significant differences in gait velocity across all monitored time periods were reported in ten articles^(6, 11, 15-17, 19, 23, 24, 26, 29), whereas significant differences were reported in 13 articles^(7, 12-14, 20-22, 25, 27, 28, 30, 38, 41); the most common differences were found with concussed individuals having a slower gait velocity at < 72 h after injury ($n = 7$)^(7, 12-14, 21, 22, 41) and 5–7 days after injury ($n = 5$)^(7, 22, 25, 27, 28). Concussed subjects had a slower gait velocity in four articles^(6, 7, 11, 15), yet this difference was not enough to be considered significant.

In terms of the stride/step parameters (length, time, width), stride/step length seemed to be the more sensitive of the measures, with six out of 12 research groups reporting significant differences between concussed and non-concussed gait^(11, 12, 25, 27, 30, 38). Significant differences in stride/step length were reported at < 72 h post-concussion ($n = 2$)^(11, 12), 5–7 days ($n = 2$)^(26, 27), 2 weeks ($n = 2$)^(12, 38) and with historic concussions ($n = 2$)^(30, 38). Five research groups utilised stride time, with two groups reporting significant differences at < 72 h post-concussion^(13, 14) and one group reporting significant differences with historic concussion⁽³⁰⁾. All eight of the articles that reported stride/step width measures found no significant differences^(6, 11-14, 17, 21, 24).

Table 3: Variables and Outcome Measures in Reviewed Articles

Description of significant findings regarding variables and outcome measures of interest over time.

Variables	Time Period Since Concussion Sustained									
	<72 h	5–7 Days		2 Weeks		1 Month	2 Months	Historic Concussion ^d		
Gait velocity ^a	↔ [7,25,28,29]	↓ [9,13,19,23,26,27,41]	↔ [7,13,28,29,33,41]	↓ [9,19,32,34,35]	↔ [7,9,13,28,29,40,41]	↓ [19]	↔ [7,9,13,19,28,29,41]	↔ [7,9,19,41]	↔ [11,12,17,37,38]	↓ [40,42,43]
Stride length ^b	↔ [7,23,26,27]	↓ [13,25]	↔ [7,13]	↓ [32,35]	↔ [7]	↓ [13,40]	↔ [7,13]	↔ [7]	↔ [12,38]	↓ [40,43]
Stride time	↔ [13,25]	↑ [26,27]	↔ [13]		↔ [13]		↔ [13]			↑ [43]
Stride width ^c	↔ [7,13,23,25–27]		↔ [7,13]		↔ [7,13]		↔ [7,13]	↔ [7]		↔ [12,38]
Cadence			↔ [32]		↓ [35]		↔ [40]			↓ [40]
Double support %					↔ [40]				↔ [38,40]	↑ [12,43]

Note: ↑ significant increase, ↓ significant decrease, ↔ no significant change, compared to control group. ^a includes results for average gait velocity, normalised gait velocity and maximal gait speed. ^b includes results for stride length and step length. ^c includes results for stride width and step width. ^d participants with a history of concussion.

Regarding cadence and double support, there was a paucity of researchers investigating the sensitivity of these measures over time, with double supporting having largely been discussed with historic concussion subjects only ($n = 4$)^(17, 24, 30, 38). Two out of four articles which included double support analysis found a significant increase in double support duration for historically concussed individuals^(17, 30).

Of the five articles that used IMUs to differentiate between concussed and non-concussed subjects, significant differences were reported regarding gait speed ($n = 5$)^(25, 27, 28, 30, 38), stride length ($n = 4$)^(25, 27, 30, 38), cadence ($n = 2$)^(27, 38), stride time ($n = 1$)⁽³⁰⁾ and double support ($n = 1$)⁽³⁰⁾.

2.4.7 Reliability

None of the studies reviewed established the reliability of the specific protocols they implemented. Four of the articles reviewed referred to reliability of the equipment and protocols established in other studies (Table 4). On reviewing these studies, two research groups investigated the reliability of GAITRite walkway variables, which only one reviewed article used⁽¹⁷⁾. Montero-Odasso et al.⁽⁴²⁾ considered gait velocity, step length, stride length, step time, stride time and double support time in single and dual task walking with a cognitively impaired elderly population (average age 76.6 ± 7.3 y). The absolute consistency (coefficient of variation (CV)) ranged from 6.36–18.28% for ST and 11.02–19.27% for DT. In terms of relative consistency, intraclass correlation coefficient (ICC) ranged from 0.80–0.97 for ST and 0.93–0.97 for DT. The GAITRite walkway was also investigated by Paterson et al.⁽⁴³⁾, however, the comparison was between younger (20.08 ± 0.7 y) and older (67.93 ± 7.8 y) populations. CVs ranged from 2.33–4.08 %. In terms of relative consistency, ICCs ranged from 0.66–0.94.

The GAITRite walkway was also utilised in conjunction with inertial sensors to establish reliability of other technologies using continuous walking protocols. Moore et al.⁽⁴⁴⁾ sought to establish the reliability of a wearable accelerometer (AX3) with stroke patients. Within the variables of step velocity, step length, step time, and stance time, the absolute agreement was good (ICC: 0.744–0.797) between AX3 and GAITRite, and moderate–excellent (ICC: 0.831–0.923) between AX3 and Opal inertial sensors. Morris et al.⁽⁴⁵⁾ compared GAITRite with Opal inertial sensor data analysed via Mobility Lab across young adults, older adults and adults with Parkinson’s disease. Gait velocity, stride length, cadence and stride time had moderate–excellent absolute agreement (ICC: 0.741–0.998); however, double support time had poor absolute agreement (ICC: 0.213–0.716).

To establish reliability of cognitive tasks while walking, Howell et al.⁽³⁷⁾ used IMUs to investigate the ST and DT gait of collegiate athletes in both contact and non-contact sports (19.2 ± 1 y)

through gait speed, cadence and stride length. This research group only reported relative consistency: the ICCs ranged from 0.68–0.80 for ST and 0.73–0.85 for DT walking.

Table 4: Reliability Articles

Description of the reliability articles cited in the reviewed articles.

Author (Year) Subjects Referenced by	Protocol Equipment	Variables	Reliability
Paterson et al. (2008) ⁽⁴³⁾ “Younger (Y)” <i>n</i> = 13 F 20.08 ± 0.7 y “Older (O)” <i>n</i> = 14 F 67.93 ± 7.8 y Reported by Martini et al. (2011) ⁽¹⁷⁾	Two test session days 7 days apart. Single and continuous walking protocols, presented in a random order. Ten walks of 3–5 gait cycles per trial recorded. Two familiarisation trials performed before data collection. Single walking trial: walk along GAITRite at self-selected walking pace. Every second walk was in the opposite position. Continuous walking: curvilinear circuit at preferred speed, walking same direction for each trial. Rest approx. 15 s between trials. Testing in laboratory. Participants wore comfortable walking shoes with a heel less than 2.5 cm. GAITRite 810 × 89 × 0.625 cm. 12 sensor pads, 27,648 sensors placed 1.27 cm apart. 80 Hz.		Inter-Session (Single and continuous trials) Y= younger O = older
		Gait velocity	CV: Y = 4.68, 4.50; O = 4.77, 4.48 ICC: Y = 0.85, 0.81; O = 0.92, 0.93
		Step length (L)	CV: Y = 2.50, 2.06; O = 2.84, 2.47 ICC: Y = 0.94, 0.95; O = 0.94, 0.95
		Step length (R)	CV: Y = 2.56, 2.36; O = 2.61, 2.44 ICC: Y = 0.93, 0.94; O = 0.93, 0.94
		Step time (L)	CV: Y = 2.50, 2.43; O = 3.56, 3.34 ICC: Y = 0.87, 0.86; O = 0.87, 0.87
		Step time (R)	CV: Y = 2.71, 2.21; O = 3.56, 3.78 ICC: Y = 0.87, 0.90; O = 0.86, 0.86
		Step width (L)	CV: Y = NA; O = NA ICC: Y = 0.74, 0.74; O = 0.66, 0.66

		Step width (R)	CV: Y = NA; O = NA ICC: Y = 0.75, 0.71; O = 0.71, 0.70
		Stance time (L)	CV: Y = 3.40, 2.60; O = 3.97, 4.02 ICC: Y = 0.86, 0.90; O = 0.91, 0.90
		Stance time (R)	CV: Y = 3.31, 2.76; O = 3.77, 3.51 ICC: Y = 0.87, 0.89; O = 0.92, 0.92
Inter-Session (Week 1 and 2)			
<p>Montero-Odasso et al. (2009)⁽⁴²⁾ C n = 11, 6 F, 5 M 76.6 ± 7.3 y Diagnosed with mild cognitive impairment Reported by Martini et al. (2011)⁽¹⁷⁾.</p>	<p>ST: walk one length of walkway at a self-selected pace. DT: walk one length while counting backwards from 100 by 1 out loud Testing in a hallway. Three trials per condition per session. Two sessions spaced one week apart. Mean of three trials used for analysis. GAITRite walkway (600 cm long and 64 cm wide)</p>	Gait velocity	CV: ST = 16.96, 13.49; DT = 17.82, 15.63 ICC: ST = 0.87; DT = 0.93
		Step length	CV: ST = 18.26, 16.65; DT = 19.27, 16.21 ICC: ST = 0.97; DT = 0.97
		Stride length	CV: ST = 18.28, 16.51; DT = 19.20, 16.51 ICC: ST = 0.97; DT = 0.97
		Step time	CV: ST = 7.27, 7.02; DT = 11.86, 12.07 ICC: ST = 0.87; DT = 0.96
		Stride time	CV: ST = 6.36, 7.08; DT = 11.02, 11.21 ICC: ST = 0.86; DT = 0.96

		Double support time	CV: ST = 12.90, 12.50; DT = 17.65, 14.71 ICC: ST = 0.80; DT = 0.95
Howell et al. (2017) ⁽⁹⁾ Subject subset <i>n</i> = 28, 17 F, 11 M 19.2 ± 1 y Concussion Classification: History self-reported University athletes Referenced by Howell et al. (2018) ⁽²⁵⁾ ; Howell et al. (2019) ⁽²⁷⁾	Static task: standing static, feet together, hands on hips, eyes open, completing cognitive task for 30 s. ST: walk barefoot at a self-selected pace to a target 8–10 m away, walk around it and return to start. DT: spelling common five letter words in reverse, subtracting by sixes or sevens, reciting months in reverse order. Five trials for each condition. Inertial sensor positioned at lumbosacral junction and dorsum of both feet. Data sampled at 128 Hz. Temporal-distance variables calculated using Mobility Lab (APDM Inc., Portland, OR, USA). Session 1 preseason baseline measures, session 2 conducted 237 ± 53 days following.		ICC ST; DT
		Gait speed	ICC: 0.68; 0.77
		Cadence	ICC: 0.80; 0.85
		Stride length	ICC: 0.71; 0.73
Moore et al. (2017) ⁽⁴⁴⁾ Stroke patients <i>n</i> = 25. 4 F, 19 M 63 ± 11 y Reported by Martini et al. (2021) ⁽³⁰⁾	Two min continuous walking at a self-selected pace around a 25 m track. Two testing sessions a week apart. 2 weeks continuous usage. Wearable accelerometer (AX3, Axivity, York, UK). GAITRite instrumented walkway (CIR systems, NJ, USA) (7.0 m × 0.6 m) One accelerometer placed on lumbar spine (Opal Sensors, APDM, Inc., Portland, OR, USA). Predefined acceptance ratings for ICCs were set at excellent (≥0.900), good (0.750–0.899), moderate (0.500–0.749) and poor (<0.500).		AX3 vs. GAITRite; AX3 vs. Opal Sensor
		Step velocity	ICC: 0.744; 0.923
		Step length	ICC: -0.411; 0.831
		Step time	ICC: 0.797; 0.890
		Stance time	ICC: 0.758; 0.876
			AX3 test-retest reliability
		Step velocity	ICC: 0.534

		Step length	ICC: 0.419
		Step time	ICC: 0.844
		Stance time	ICC: 0.819
Morris et al. (2019) ⁽⁴⁵⁾			YA; OA; PD; Overall
Young adults			
$n = 18$, 10 F, 8 M		Gait velocity	ICC: 0.861; 0.934; 0.920; 0.928
27 ± 4.4 y	Barefoot walk for 2 min at a self-selected pace walking back and forth over a GAITRite walkway.	Stride length	ICC: 0.741; 0.939; 0.880; 0.908
Older adults		Cadence	ICC: 0.998; 0.996; 0.996; 0.996
$n = 18$, 10 F, 8 M	GAITRite walkway $6 \text{ m} \times 0.6 \text{ m}$.	Stride time	ICC: 0.998; 0.998; 0.992; 0.996
63.4 ± 9.5 y	Three inertial sensors (Opal Sensors, APDM, Inc., Portland, OR, USA) placed on both feet and at lumbar spine.	Double support time	ICC: 0.213; 0.716; 0.285; 0.518
Parkinson's disease			
$n = 21$, 9 F, 12 M	Mobility Lab (APDM Inc.) utilised to collect data.		
67.5 ± 8.8 y			
Reported by Martini et al. (2021) ⁽³⁰⁾			

Key: n, number; C, concussed subjects; F, female; M, male; CV, coefficient of variation; ICC, intraclass correlation coefficient; cm, centimetres; m, metres; Hz, hertz; s, seconds; ST, single task; DT, dual task.

2.5 Discussion

Concussions are an increasingly common mild traumatic brain injury that are experienced in sport. To limit misdiagnosis of individuals with concussion and to assist with return to play, there is a need for assessment protocols that incorporate both cognitive and physical elements to allow for a more accurate evaluation of concussive impairment. Assessing gait whilst performing a cognitive task is one such assessment protocol and formed the focus of this review. Of particular interest were the methodological approaches taken by various research groups and determining those protocols and/or variables that could consistently differentiate between concussed and non-concussed individuals.

The participants involved across the reviewed articles were diverse in sample size (12–122), age (12–68 y), sport (football, cheerleading, horseback riding, to name a few) and competition level (recreational–elite). Sixty-one percent of the reviewed study protocols required participants to partake barefoot, which presents an interesting issue in terms of whether testing should take place with shoes or barefoot, which potentially may affect the clinical outcomes. Counting or spelling backwards seemed to be the easiest of dual tasks to implement given the ease of administration and lack of equipment required, negating the need for extensive set up time. It is suggested that these cognitive tests should be randomised to limit any learning effects.

The most widespread use of equipment involved 3D MOCAP and force plates. While the equipment may be considered to provide more precise information, the cost of the equipment and the expertise required to run, process and analyse the data is a restrictive factor for assessing concussions outside of conducting research. A significant time cost is also involved with processing the information recorded from MOCAP and force plates to generate data for analysis. Equipment that does not require as extensive proficiency or time to process and analyse collected data, such as with inertial sensor technology, may offer a more accessible tool for practitioners in diagnosing and monitoring concussion.

The most common distance that participants were assessed over with dual task gait was 8–10 m. This was largely a result of the space in which the testing was conducted and the available equipment e.g., 2–3 force plates in series and/or in ground with 3D MOCAP. The authors feel that the set-up of such equipment is a limitation, in that testing is restricted to a particular environment (i.e., sports laboratory) which may impede the initial diagnosis and subsequent monitoring of concussed individuals, thus, being detrimental for quicker return to play. More portable technologies (i.e., IMUs) may provide a more accessible and convenient tool that can be utilised within a wide range of environments. If dual task gait analysis of concussive diagnosis is to have any real-world utility, then serious consideration of other technological approaches will be needed.

None of the 3D MOCAP and force plate outcome measures reported were found to be sensitive enough to consistently determine differences between concussed and non-concussed diagnosis during DT walking. Gait velocity, stride/step length and stride/step width were the variables that were most

reported on, with significant differences being reported by 31%^(12-14,22,41) and 25%^(11,12) of the reviewed articles for gait velocity and stride/step length, respectively, but no article was found to report significant differences in stride/step width. The majority of articles found no significant differences across the gait variables of interest. Comparatively, articles that utilised IMUs to measure gait velocity and stride/step length reported significant differences in 100%^(25, 27, 28, 30, 38) and 80%^(25, 27, 30, 38) of the articles, respectively. This may indicate that IMU utilisation enables increased accuracy and/or sensitivity due to a closer interaction with the gait movement patterns. It also needs to be noted that the diagnostic value of any gait analysis is enhanced when data is collected over multiple testing occasions. This historic data provides a better insight into any aberrations that may need addressing.

The emergence of inertial sensor technology^(25,27,28,30,38) might provide a viable alternative to MOCAP and force plate analyses. The outcome variables reported by the articles that utilised IMUs showed promising consistency in differentiating between concussed and non-concussed diagnoses. It would be interesting to understand whether different sensor placements (e.g., in-sole sensors) offer added sensitivity and accuracy, compared to the sensor arrangements in the bulk of the studies reviewed (lumbosacral, dorsum and foot).

One of the most concerning aspects of all the articles reviewed was the absence of any reporting of the reliability of the outcome measures of interest. Understanding the “noise” or unexplained variability associated with a measure is fundamental to interpreting findings. Only one research group⁽¹⁷⁾ provided evidence regarding the reliability of the GAITRite walkway in elderly and young cohorts, citing the work of Paterson et al. (2008)⁽⁴³⁾ and Montero-Odasso et al. (2009)⁽⁴²⁾. The results were markedly different in that Paterson et al.’s⁽⁴³⁾ findings were acceptable (CV < 4.08%; ICCs 0.66–0.94), whereas the absolute consistency of Montero-Odasso et al.⁽⁴²⁾ was not (DT CVs 11.02–19.27%; ICCs 0.93–0.97). This could be attributed to the age of the participants in the latter study. Nonetheless, it needs to be noted that only Martini et al.⁽¹⁷⁾ used the GAITRite walkway as a method of measuring DT gait variables and, therefore, it is problematic to make generalisations to other methodological approaches.

2.6 Conclusion

However, whether certain technologies and/or variables are better suited in discriminating between concussed and non-concussed diagnoses is unknown.

Of particular interest to the authors was understanding the methodological approaches taken by various research groups and determining those variables that could consistently and reliably differentiate between concussed and non-concussed individuals. In terms of the first foci, MOCAP and force plates were the dominant technologies used to quantify concussed and non-concussed gait. From the literature reviewed, it would seem that none of the gait parameters assessed using MOCAP and

force plates used to quantify concussed and non-concussed gait impairments were consistently sensitive enough to determine significant differences between groups, particularly over various time periods/testing occasions. This may mean two things: (1) DT walking is not sufficiently sensitive enough as an assessment to determine concussive diagnosis consistently; or (2) the protocols/technologies that are being used need refining or replacing to enable better concussion detection. For example, it would be interesting to determine if longer distances/large fields of capture enabled better precision of measurement.

With regards to the consistency and reliability of data, there seems to be little attention in the research reviewed on the variability of the measures utilised to quantify gait characteristics. Fundamental to research going forwards, especially with new and innovative technology, is establishing the reliability and smallest worthwhile changes in gait parameters.

Inertial sensor technology has been used in a few studies to date with some promising results around average gait speed and stride length. However, as with the other technologies reviewed, the reliability has not been documented and there may be better placement of sensors than the lumbar and dorsum but researchers have provided a starting point for ongoing investigation. For example, it would be interesting to determine if inertial sensors that quantify the foot-ground interaction (e.g., inner sole sensors) offer any diagnostic benefits in this area.

Finally, the cost of MOCAP and force plates and the expertise required to run, process and analyse the data is a restrictive factor for assessing concussions outside of conducting research. It is believed that the advent of technological “solutions” such as inertial sensors may enable dual task testing outside of the laboratory given the portability of such devices. If the technology is found to be valid, reliable, accurate and sensitive to changes in gait characteristics, they may provide a viable assessment option that could result in higher utility of dual task walking assessments in the diagnosis of concussion.

Chapter 3: The Variability of Dual Task Walking Parameters Using In-Shoe Inertial Sensors in Non-Concussed Individuals

3.1. Preface

It appears that inertial movement sensors may be a better technology at detecting gait changes in concussed individuals. Therefore, it would be beneficial to investigate whether IMU placement through closer foot-ground interaction (foot pods) might be a reliable technology for quantifying various gait parameters in non-concussed individuals.

3.2. Introduction

Concussion is an increasingly common mild traumatic brain injury that can occur during sport that are frequently missed or underestimated 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 ^(6-9,46). 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 ^(6,7,9,11-29). Much of the research in this area has used 3D MOCAP and force plate technology to differentiate determine the influence of concussion diagnosis on gait parameters ^(6,7,11-16,18-24,26). A recent review, however, has pointed out that none of the gait parameters (gait velocity, stride length, etc.) measured by these devices were found to be sensitive enough to consistently determine differences between concussed and non-concussed diagnoses ⁽⁴⁷⁾. 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 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 analyse the data, which preclude concussion assessment outside of a well-funded research environment.

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^(9,25,27,28,30). However, the reliability has not been documented and there may be better placement of sensors than the lumbar and dorsum of feet sites utilised in the research to date, but researchers have provided a starting point for ongoing investigation. For example, it would be interesting to determine if inertial sensors that quantify the foot-ground interaction (e.g., inner sole sensors) offer any diagnostic benefits 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 hypothesised that gait speed and stride length would show acceptable test-retest reliability. The secondary aim of this research was to determine if gait parameters are different across the 12 m, 30 m, and 1 minute out and back testing conditions. It was hypothesised that the greater straight-line distances associated with the 1 minute out and back protocol would be less variable than both the 12 m and 30 m protocols. Understanding the variability and smallest worthwhile changes in non-concussed 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 may provide a viable assessment option 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.

3.3. Methods

3.3.1. Experimental Approach to the Problem

This study used a within-subject repeated measures design, where participants performed a 2-minute 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 minute out and back. The same session was completed over three testing occasions separated by seven 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 randomised trials⁽⁴⁸⁾.

3.3.2. Participants

Twenty participants (8 females/11 males) (age: 35.2 ± 16.1 y; 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 (Appendix B), participants provided their signed informed consent prior to 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).

3.3.3. Procedures

Piloting was undertaken prior to 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 i.e., 2 minutes of 12 m, 30 m, and 1 minute 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 seven days apart, at approximately the same time of day, under similar experimental conditions. During each testing session, participants performed 2-minute continuous walking assessments while performing a cognitive task during the three protocols. The cognitive task involved participants, prior to initiating each trial, receiving a random number between 300 – 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 non-concussed populations ^(11, 14, 18, 21, 28).

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 towards a cone placed at 12 m and 30 m, respectively. 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 two minutes. Participants were free to choose which way to navigate the cone but were instructed to navigate the cones the same way throughout all of the testing and over the three testing occasions.

For the 1 minute 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 minute of continuous walking, the participant was instructed to turn around and head back towards the start for a further minute. 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 two minutes 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 randomised for each participant.

3.3.4. Equipment

To quantify gait variables, two inertial measurement sensors (Plantiga Insoles; Vancouver, Canada) were placed in the participants' shoes. Inertial measurement sensors are a valid technology for measuring spatial-temporal gait parameters^(49,50) that has been utilised to monitor gait performance among individuals with physiological conditions that may cause gait and balance impairments^(49,51,52). Data were obtained at a sampling frequency of 416 Hz, time synchronised, and uploaded to a laptop computer following each testing occasion. Two cones were used for each respective test. The random number between 300-500 was generated using an online random number generator (random.org, Randomness and Integrity Services Ltd, Dublin, Ireland).

3.3.5. Data Analysis

The primary outcome was to determine the variability of dual task walking gait parameters using in-shoe inertial sensors in non-concussed 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 (left/right/total (overall average stride length)) (m), ground contact time (left/right/total (overall average contact time)) (ms), and double support (%). Each outcome was calculated using the associated Plantiga online software.

3.3.6. 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 analysed using IBM SPSS statistical software package (version 28.0, IBM Corporation, New York, USA). Data was 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 determine if systematic differences were present between testing sessions one to two

and two to three, dependent t-tests were used, with statistical significance set at $p < .05$. Absolute consistency between sessions was assessed using a specifically designed Excel (Microsoft 365, version 2202, Microsoft Corporation, Redmond, WA, USA) spreadsheet from sportsci.org^(53,54) to quantify reliability. Relative consistency using test-retest correlations was measured via ICC using a two-way random model and average measures⁽⁵⁵⁾. CVs of less than 10% were deemed acceptable as a percent of typical error⁽⁵⁶⁾. 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)⁽⁵⁷⁾.

3.4. Results

Means, SD, % change in the mean CV and the ICC for the three protocols can be seen in Table 5, Table 6, and Table 7. 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 regards to the absolute consistency between testing occasions, CVs ranged from 2.3 to 4.8%, the largest variability was associated with 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).

Table 5: Descriptive Statistics for 12 m Protocol

	Mean (± SD)		% change of mean (95% CL)		CV (95% CL)		ICC (95% CL)		
	<i>Day 1</i>	<i>Day 2</i>	<i>Day 3</i>	<i>Day 1-2</i>	<i>Day 2-3</i>	<i>Day 1-2</i>	<i>Day 2-3</i>	<i>Day 1-2</i>	<i>Day 2-3</i>
<i>Gait speed (m/s)</i>	1.20 (0.13)	1.23 (0.12)	1.23 (0.11)	2.8 (0.2 – 0.55)	-0.5 (-2.9 – 2.0)	4.8 (3.8-6.6)	4.6 (3.6-6.3)	0.83 (0.66 – 0.92)	0.80 (0.62 – 0.90)
<i>Cadence (steps/min)</i>	105.25 (4.55)	107.08 (6.25)	106.38 (7.10)	1.1 (-0.2 – 2.4)	-0.7 (-2.0 – 0.6)	2.4 (1.9 – 3.3)	2.5 (2.0 – 3.4)	0.83 (0.67 – 0.92)	0.87 (0.73 – 0.94)
<i>Stride length (m)</i>									
<i>Overall</i>	1.36 (0.11)	1.38 (0.11)	1.37 (0.10)	1.4 (-0.2 – 3.0)	-0.3 (-1.9 – 1.4)	2.9 (2.3 – 3.9)	3.1 (2.5 – 4.3)	0.89 (0.78 – 0.95)	0.85 (0.71 – 0.93)
<i>Left</i>	1.35 (0.11)	1.37 (0.11)	1.35 (0.12)	1.4 (-0.1 – 3.0)	-1.0 (-3.5 – 1.5)	2.9 (2.3 – 3.9)	4.8 (3.8 – 6.6)	0.89 (0.77 – 0.95)	0.69 (0.43 – 0.84)
<i>Right</i>	1.37 (0.12)	1.39 (0.11)	1.39 (0.11)	1.2 (-0.4 – 2.9)	-0.2 (-1.8 – 1.4)	3.0 (2.4 – 4.1)	2.9 (2.3 – 4.0)	0.88 (0.76 – 0.94)	0.87 (0.74 – 0.94)
<i>Ground contact time (ms)</i>									
<i>Overall</i>	704.70 (56.96)	689.25 (48.96)	693.05 (49.51)	-2.1 (-3.8 - -0.4)	0.6 (-0.7 – 1.9)	3.2 (2.5 – 4.4)	2.4 (1.9 – 3.3)	0.85 (0.70 – 0.93)	0.90 (0.80 – 0.95)
<i>Left</i>	704.10 (55.85)	689.00 (48.18)	695.35 (53.74)	-2.1 (-3.7 - -0.4)	0.9 (-0.6 – 2.4)	3.1 (2.5 – 4.3)	2.8 (2.2 – 3.8)	0.85 (0.70 – 0.93)	0.87 (0.74 – 0.94)
<i>Right</i>	704.60 (57.67)	689.90 (50.63)	692.35 (49.03)	-2.0 (-3.7 - -0.3)	0.4 (-0.9 – 1.7)	3.2 (2.5 – 4.4)	2.3 (1.8 – 3.2)	0.86 (0.71 – 0.93)	0.91 (0.81 – 0.96)
<i>Double support (%)</i>	22.21 (2.97)	21.98 (2.77)	22.15 (2.91)	-0.9 (-3.1 – 1.2)	0.7 (-1.1 – 2.5)	4.0 (3.2 – 5.6)	3.3 (2.6 – 4.6)	0.92 (0.82 – 0.96)	0.94 (0.87 – 0.97)
<i>Overall average</i>				1.67	0.59				

Note: Data are mean ± SD of each variable with the difference between sessions with the percent (%) difference given with the 90% confidence interval.

Table 6: Descriptive Statistics for 30 m Protocol

	Mean (\pm SD)			% change of mean (95% CL)		CV (95% CL)		ICC (95% CL)	
	<i>Day 1</i>	<i>Day 2</i>	<i>Day 3</i>	<i>Day 1-2</i>	<i>Day 2-3</i>	<i>Day 1-2</i>	<i>Day 2-3</i>	<i>Day 1-2</i>	<i>Day 2-3</i>
<i>Gait speed (m/s)</i>	1.28 (0.15)	1.30 (0.12)	1.28 (0.13)	2 (-0.3 – 4.4)	-1.3 (-4.0 – 1.4)	4.3 (3.4 – 5.9)	5.1 (4.0 – 7.1)	0.86 (0.71 – 0.93)	0.75 (0.53 – 0.88)
<i>Cadence (steps/min)</i>	107.65 (6.85)	108.72 (7.01)	109.04 (5.79)	1.0 (-0.8 – 2.8)	0.4 (-0.7 – 1.5)	3.3 (2.6 – 4.6)	2.0 (1.6 – 2.8)	0.76 (0.54 – 0.88)	0.90 (0.79 – 0.95)
<i>Stride length (m)</i>									
<i>Overall</i>	1.42 (0.12)	1.42 (0.12)	1.41 (0.12)	0.5 (-1.0 – 2.0)	-1.1 (-3.0 – 0.9)	2.7 (2.2 – 3.7)	3.7 (2.9 – 5.1)	0.91 (0.81 – 0.96)	0.81 (0.63 – 0.91)
<i>Left</i>	1.40 (1.12)	1.42 (1.12)	1.39 (1.3)	0.9 (-0.5 – 2.3)	-2.0 (-5.2 – 1.3)	2.6 (2.1 – 3.6)	6.3 (5.0 – 8.7)	0.92 (0.82 – 0.96)	0.53 (0.2 – 0.75)
<i>Right</i>	1.43 (0.13)	1.44 (0.12)	1.42 (0.12)	0.7 (-0.8 – 2.3)	-1.2 (-3.1 – 0.7)	2.8 (2.3 – 3.9)	3.6 (2.8 – 4.9)	0.90 (0.80 – 0.95)	0.84 (0.68 – 0.92)
<i>Ground contact time (ms)</i>									
<i>Overall</i>	685.85 (56.32)	673.25 (44.39)	676.00 (47.98)	-1.7 (-3.3 – -0.1)	0.4 (-0.5 – 1.3)	3.1 (2.4 – 4.2)	1.7 (1.4 – 2.4)	0.85 (0.70 – 0.93)	0.94 (0.88 – 0.97)
<i>Left</i>	686.05 (55.03)	672.95 (43.03)	679.15 (51.77)	-1.8 (-3.4 – -0.2)	0.9 (-0.5 – 2.2)	3.0 (2.4 – 4.2)	2.4 (1.9 – 3.4)	0.85 (0.70 – 0.93)	0.89 (0.78 – 0.95)
<i>Right</i>	686.35 (58.32)	673.40 (45.70)	674.15 (49.33)	-1.8 (-3.5 – 0.0)	0.1 (-0.9 – 1.1)	3.2 (2.6 – 4.5)	1.8 (1.4 – 2.5)	0.85 (0.69 – 0.93)	0.94 (0.88 – 0.97)
<i>Double support (%)</i>	21.23 (3.18)	21.08 (2.70)	21.27 (3.03)	0.1 (-2.6 – 2.9)	0.7 (-1.2 – 2.7)	5.2 (4.1 – 7.2)	3.6 (2.9 – 5.0)	0.88 (0.76 – 0.94)	0.94 (0.87 – 0.97)
<i>Overall average</i>				1.17	0.9				

Note: Data are mean \pm SD of each variable with the difference between sessions with the percent (%) difference given with the 90% confidence interval.

Table 7: Descriptive Statistics for 1 min Out Protocol

	Mean (± SD)			% change of mean (95% CL)		CV (95% CL)		ICC (95% CL)	
	Day 1	Day 2	Day 3	Day 1-2	Day 2-3	Day 1-2	Day 2-3	Day 1-2	Day 2-3
<i>Gait speed (m/s)</i>	1.24 (0.15)	1.26 (0.14)	1.25 (0.13)	1.3 (-0.6 – 3.2)	-0.6 (-2.8 – 1.6)	3.5 (2.8 – 4.8)	4.1 (3.3 – 5.7)	0.92 (0.84 – 0.96)	0.87 (0.74 – 0.94)
<i>Cadence (steps/min)</i>	106.95 (6.63)	107.57 (6.47)	105.62 (7.70)	0.3 (-1.0 – 1.6)	-1.6 (-2.9 – -0.3)	2.4 (1.9 – 3.4)	2.5 (1.9 – 3.4)	0.86 (0.71 – 0.93)	0.89 (0.77 – 0.95)
<i>Stride length (m)</i>									
<i>Overall</i>	1.40 (0.14)	1.41 (0.13)	1.40 (0.13)	0.7 (-0.5 – 1.9)	-0.3 (-1.9 – 1.4)	2.2 (1.7 – 3.0)	3.0 (2.4 – 4.1)	0.95 (0.90 – 0.98)	0.90 (0.80 – 0.95)
<i>Left</i>	1.38 (1.3)	1.39 (0.13)	1.38 (0.11)	1.0 (-0.3 – 2.2)	-0.6 (-2.1 – 1.0)	2.3 (1.8 – 3.1)	3.0 (2.4 – 4.1)	0.95 (0.89 – 0.98)	0.89 (0.78 – 0.95)
<i>Right</i>	1.42 (0.14)	1.42 (0.14)	1.43 (0.13)	0.6 (-0.7 – 1.8)	0.4 (-1.4 – 2.3)	2.3 (1.8 – 3.2)	3.4 (2.7 – 4.7)	0.95 (0.90 – 0.98)	0.88 (0.76 – 0.94)
<i>Ground contact time (ms)</i>									
<i>Overall</i>	690.90 (58.03)	673.25 (44.39)	690.00 (50.23)	-2.4 (-4.8 – 0.0)	3.5 (1.6 – 5.4)	4.6 (3.6 – 6.4)	3.4 (2.7 – 4.7)	0.67 (0.40 – 0.83)	0.79 (0.59 – 0.90)
<i>Left</i>	691.80 (58.29)	685.20 (45.42)	697.40 (49.69)	-0.8 (-2.2 – 0.5)	1.8 (0.6 – 2.9)	2.5 (2.0 – 3.4)	2.1 (1.7 – 2.9)	0.91 (0.81 – 0.96)	0.92 (0.83 – 0.96)
<i>Right</i>	689.90 (58.66)	685.15 (47.05)	696.80 (51.35)	-0.6 (-2.0 – 0.8)	1.7 (0.6 – 2.8)	2.6 (2.0 – 3.6)	2.0 (1.6 – 2.8)	0.90 (0.80 – 0.95)	0.93 (0.85 – 0.97)
<i>Double support (%)</i>	21.03 (3.33)	21.20 (3.03)	21.86 (3.35)	1.0 (-1.9 – 4.0)	3.0 (1.1 – 5.0)	5.5 (4.3 – 7.6)	3.5 (2.8 – 4.9)	0.89 (0.77 – 0.95)	0.95 (0.90 – 0.98)
<i>Overall average</i>				0.97	1.5				

Note: Data are mean ± SD of each variable with the difference between sessions with the percent (%) difference given with the 90% confidence interval.

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 minute 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. The average percent change across all outcomes of interest between testing occasions was 0.97 and 1.5%. With regards 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 8. 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.

Table 8: Reliability Statistics for Each Protocol

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

3.5. Discussion

DT assessments of concussion are common in the literature and typically use 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. Prior to determining its utility in

quantifying concussed gait parameters, it would be prudent to determine the expected variability associated with non-concussed 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 i.e., only three variables were < 0.70 ; and, 3) the variability across the three protocol distances was similar. With regards 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 minute out and back protocol would have the least variability was unfounded.

Coefficients of variation are deemed acceptable when they are less than 10% ⁽⁵⁸⁾. 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. There is a paucity of research groups who have investigated similar DT walking protocols using other technologies who have reported the reliability of their respective protocols, so it is difficult to compare our results. However, one research group ⁽¹⁷⁾ did provide reliability statistics for two comparable walking protocols using GAITRite technology. The GAITRite walkway is 0.89 x 8.3 m and imbedded with 13,824 sensors that allowed for calculation of temporal and spatial gait parameters. Montero-Odasso et al. ⁽⁴²⁾ reported CVs ranging from 11.02 – 19.27% for outcome variables during DT gait, and Paterson et al. ⁽⁴³⁾ reported CVs ranging from 2.06 – 4.77%. Montero-Odasso et al.'s research involved older adults aged 70+ y, and Paterson et al. involved both young (~20 y) 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 ⁽⁵⁵⁾ 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. ⁽⁴²⁾ reported ICCs of 0.93 or higher when assessing DT gait, whereas Paterson et al. ⁽⁴³⁾ reported a much larger range of ICCs (0.66 – 0.94) for the GAITRite technology. Howell et al. ⁽³⁷⁾ and Howell et al. ⁽⁵⁹⁾ examined the test-retest reliability of a similar DT gait protocol using 3D MOCAP technology with healthy, non-concussed individuals. Over two testing sessions, Howell et al. ⁽³⁷⁾ reported ICCs ranging from 0.73 – 0.85, whereas Howell et al. ⁽⁵⁹⁾ evaluated reliability over five testing occasions, and reported ICCs between 0.79 – 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 i.e., 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 minute 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 i.e., a clearway of 12 m is all that is needed to perform this gait assessment. However, it is still recommended that one protocol is selected and used consistently, rather than using the protocols interchangeably.

There were several limitations with this research. Firstly, the sample size was relatively small ($n = 20$) but was very diverse in terms of sporting background, age and gender. This was purposeful given that the subjects used in concussive research are equally diverse; however, the variability may vary across the testing conditions within larger samples and sport specific cohorts. Secondly, the test is very easy to administer from data collection to data download; however, it still may be of interest to determine inter-rater reliability. 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.

3.6. Conclusion

Most of the technology used for the DT assessments of concussion at this point in time are relatively inaccessible and unaffordable to most practitioners, hence the need to find technology and protocols that are cost-effective and of high utility. The in-shoe inertial sensors provide one such option given the results of this study. Alongside the reliability of the technology is the knowledge that the DT 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. Finally, the value of the innersole inertial sensor technology in monitoring concussive gait needs to be investigated.

Chapter 4: Summary, Practical Recommendations and Future Research Directions

4.1 Summary

The preliminary aim of this dissertation was to examine the literature and determine what technologies and methods were used to differentiate between concussive and non-concussive gait. The literature review (Chapter 2) discussed what outcome measures, testing protocols, and equipment were used to differentiate between concussed states. Motion capture (MOCAP) and force plates were considered to be gold standard technologies, however, there had been very little research to verify the validity and/or reliability of this equipment regarding dual-task gait assessments. Five studies utilised inertial sensors to assess gait parameters, the findings of these researchers suggesting that there is potential for more cost-effective, high-utility, and user-friendly technology to be used in place of 3D MOCAP and force plates. A wide range of outcome variables were utilised across the reviewed studies; however, none were deemed to be sensitive enough to consistently determine gait differences in concussive status.

The primary aim of this dissertation was then to investigate the variability of dual task walking gait parameters using in-shoe inertial sensors in non-concussed individuals. From this investigation we found there to be: 1) acceptable absolute consistency between testing sessions for all variables; 2) acceptable relative consistency (ICCs > 0.70) amongst all but three variables of interest (*12 m protocol*: left average stride length day 2-3; *30 m protocol*: left average stride length day 2-3; *1 min out protocol*: average stride length day 1-2); and, 3) similar variability across the three testing protocols. It was determined in-shoe inertial sensors were a viable option for monitoring gait parameters, and that such technology was reliable across all three protocols (12 m, 30 m, 1 minute out and back) which can offer various testing options for practitioners.

4.2 Practical Recommendations

In-shoe inertial sensors offer a more affordable and accessible technology to monitor changes in gait during dual task walking. Given that this study incorporated healthy, uninjured participants, it is recommended that concussed individuals are recruited to determine reliability and variability amongst this particular population.

4.3 Future Research

A number of areas are recommended for future investigation:

- This research has provided reliability information on gait parameters in non-concussed individuals using in-shoe inertial sensors. Further research should be performed using the same methodology of this study, but instead recruiting concussed individuals and determining the variability within this specific population group.
- Given that the data collected in this research was gathered by a single researcher, there should be further investigation into inter-tester reliability to determine if there is any variance between test administrators.
- Researchers should also investigate whether there is any variability when the three distance protocols are used interchangeably. Such data may offer an indication of the practicality of using these protocols and how adaptable they may or may not be.

References

1. Herman DC, Jones D, Harrison A, Moser M, Tillman S, Farmer K, et al. Concussion may increase the risk of subsequent lower extremity musculoskeletal injury in collegiate athletes. *Sports Medicine*. 2017;47(5):1003-10.
2. Howell DR, Lynall RC, Buckley T, Herman DC. Neuromuscular control deficits and the risk of subsequent injury after a concussion: A scoping review. *Sports Medicine*. 2018;48(5):1097-115.
3. Cantu RC. Dysautoregulation/second-impact syndrome with recurrent athletic head injury. *World Neurosurgery*. 2016;95(1):601-2.
4. Cantu RC, Uretsky M. Consequences of ignorance and arrogance for mismanagement of sports-related concussions: Short-term and long-term complications. In: Slobounov SM, Sebastianelli WJ, editors. *Concussions in athletics: From brain to behaviour*. 2nd ed: Springer; 2021. p. 3-18.
5. McCrory P, Meeuwisse W, Dvořák J, Aubry M, Bailes J, Broglio S, et al. Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*. 2017;51(11):838-47.
6. Howell DR, Osternig LR, Chou L-S. Dual-task effect on gait balance control in adolescents with concussion. *Archives of Physical Medicine and Rehabilitation*. 2013;94(8):1513-20.
7. Howell DR, Osternig LR, Koester MC, Chou L-S. The effect of cognitive task complexity on gait stability in adolescents following concussion. *Experimental Brain Research*. 2014;232(1):1773-82.
8. Fino P. A preliminary study of longitudinal differences in local dynamic stability between recently concussed and healthy athletes during single and dual-task gait. *Journal of Biomechanics*. 2016;49(9):1983-8.
9. Howell DR, Osternig LR, Chou L-S. Single-task and dual-task tandem gait test performance after concussion. *Journal of Science and Medicine in Sport*. 2017;20(7):622-6.
10. Howell D, Kirkwood MW, Provance A, Iverson GL, Meehan WP. Using concurrent gait and cognitive assessments to identify impairments after concussion: A narrative review. *Concussion*. 2018;3(1).
11. Parker T, Osternig LR, Lee H-J, Van Donkelaar P, Chou L-S. The effect of divided attention on gait stability following concussion. *Clinical Biomechanics*. 2005;20(4):389-95.
12. Parker T, Osternig LR, Van Donkelaar P, Chou L-S. Gait stability following concussion. *Medicine & Science in Sports & Exercise*. 2006;38(6):1032-40.
13. Catena R, Van Donkelaar P, Chou L-S. Cognitive task effects on gait stability following concussion. *Experimental Brain Research*. 2007;176(23):23-31.
14. Catena R, Van Donkelaar P, Chou L-S. Altered balance control following concussion is better detected with an attention test during gait. *Gait & Posture*. 2007;25(3):406-11.
15. Parker T, Osternig LR, Van Donkelaar P, Chou L-S. Recovery of cognitive and dynamic motor function following concussion. *British Journal of Sports Medicine*. 2007;41(2):868-73.

16. Parker T, Osternig LR, Van Donkelaar P, Chou L-S. Balance control during gait in athletes and non-athletes following concussion. *Medical Engineering & Physics*. 2008;30(8):959-67.
17. Martini DN, Sabin MJ, DePesa SA, Leal EW, Negrete TN, Sosnoff JJ, et al. The chronic effects of concussion on gait. *Archives of Physical Medicine and Rehabilitation*. 2011;92(4):585-9.
18. Chiu S-L, Osternig LR, Chou L-S. Concussion induces gait inter-joint coordination variability under conditions of divided attention and obstacle crossing. *Gait & Posture*. 2013;38(4):717-22.
19. Fait P, Swaine B, Cantin J-F, Leblond J, McFadyen BJ. Altered integrated locomotor and cognitive function in elite athletes 30 days postconcussion: A preliminary study. *The Journal of Head Trauma Rehabilitation*. 2013;28(4):293-301.
20. Cossette I, Ouellet M-C, McFadyen BJ. A preliminary study to identify locomotor-cognitive dual tasks that reveal persistent executive dysfunction after mild traumatic brain injury. *Archives of Physical Medicine and Rehabilitation*. 2014;96(8):1594-7.
21. Chen H-L, Lu T-W, Chou L-S. Effect of concussion on inter-joint coordination during divided-attention gait. *Journal of Medical and Biological Engineering*. 2015;35(1):28-33.
22. Howell DR, Osternig LR, Chou L-S. Monitoring recovery of gait balance control following concussion using an accelerometer. *Journal of Biomechanics*. 2015;48(12):3364-8.
23. Cossette I, Gagne M-E, Ouellet M-C, Fait P, Gagnon I, Sirois K, et al. Executive dysfunction following a mild traumatic brain injury revealed in early adolescence with locomotor-cognitive dual-tasks. *Brain Injury*. 2016;30(13-14):1648-55.
24. Martini DN, Goulet GC, Gates DH, Broglio SP. Long-term effects of adolescent concussion history on gait, across age. *Gait & Posture*. 2016;49(1):264-70.
25. Howell DR, Stillman A, Buckley T, Berkstresser B, Wang F, Meehan WP. The utility of instrumented dual-task gait and tablet-based neurocognitive measurements after concussion. *Journal of Science and Medicine in Sport*. 2018;21(4):358-62.
26. Solomito MJ, Kostyun RO, Wu Y-H, Mueske NM, Wren TAL, Chou L-S, et al. Motion analysis evaluation of adolescent athletes during dual-task walking following a concussion: A multicenter study. *Gait & Posture*. 2018;64(1):260-652.
27. Howell D, Buckley T, Berkstresser B, Wang F, Meehan WP. Identification of postconcussion dual-task gait abnormalities using normative reference values. *Journal of Applied Biomechanics*. 2019;35(4):290-6.
28. Howell D, Myer GD, Grooms D, Diekfuss J, Yuan W, Meehan WP. Examining motor tasks of differing complexity after concussion in adolescents. *Archives of Physical Medicine and Rehabilitation*. 2019;100(4):613-9.
29. Gagne M-E, McFadyen BJ, Ouellet M-C. Performance during dual-task walking in a corridor after mild traumatic brain injury: A potential functional marker to assist return-to-function decisions. *Brain Injury*. 2021;35(2):173-9.

30. Martini DN, Parrington L, Stuart S, Fino PC, King LA. Gait performance in people with symptomatic, chronic mild traumatic brain injury. *Journal of Neurotrauma*. 2021;38(2):218-24.
31. Catena R, Van Donkelaar P, Chou L-S. The effects of attention capacity on dynamic balance control following concussion. *Journal of NeuroEngineering and Rehabilitation*. 2011;8:1-8.
32. Howell DR, Osternig LR, Chou L-S. Adolescents demonstrate greater gait balance control deficits after concussion than young adults. *The American Journal of Sports Medicine*. 2015;43(3).
33. Howell DR, Osternig LR, Chou L-S. Return to activity after concussion affects dual-task gait balance control recovery. *Medicine & Science in Sports & Exercise*. 2015;47(4):673-80.
34. Catena R, Van Donkelaar P, Chou L-S. Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. *Journal of NeuroEngineering and Rehabilitation*. 2009;6(25).
35. Catena R, van Donkelaar P, Haltermann CI, Chou L-S. Spatial orientation of attention and obstacle avoidance following concussion. *Experimental Brain Research*. 2009;194(1):67-77.
36. Howell DR, Stracciolini A, Geminiani E, Meehan WP. Dual-task gait differences in female and male adolescents following sport-related concussion. *Gait & Posture*. 2017;54(1):284-9.
37. Howell DR, Oldham JR, DiFabio M, Vallabhajousula S, Hall EE, Ketcham CJ, et al. Single-task and dual-task gait among collegiate athletes of different sport classifications: Implications for concussion measurement. *Journal of Applied Biomechanics*. 2017;33(1):24-31.
38. Berkner J, Meehan WP, Master CL, Howell DR. Gait and quiet-stance performance among adolescents after concussion-symptom resolution. *Journal of Athletic Training (Allen Press)*. 2017;52(12):1089-95.
39. Howell DR, Lugade V, Taksir M, Meehan WP. Determining the utility of a smartphone-based gait evaluation for possible use in concussion management. *The Physician and Sportsmedicine*. 2020;48(1):75-80.
40. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Annals Of Internal Medicine*. 2018;169(7):467-+.
41. Yasen AL, Howell DR, Chou LS, Christie AD, Pazzaglia AM. Cortical and physical function after mild traumatic brain injury. *Medicine and Science in Sports and Exercise*. 2017;49(6):1066-71.
42. Montero-Odasso M, Casas A, Hansen KT, Bilski P, Gutmanis I, Wells JL, et al. Quantitative gait analysis under dual-task in older people with mild cognitive impairment: A reliability study. *Journal of NeuroEngineering and Rehabilitation*. 2009;6(35).
43. Paterson KL, Hill KD, Lythgo ND, Mashette W. The reliability of spatiotemporal gait data for young and older women during continuous overground walking. *Archives of Physical Medicine and Rehabilitation*. 2008;89(12):2360-5.
44. Moore SA, Hickey A, Lord S, Del Din S, Godfrey A, Rochester L. Comprehensive measurement of stroke gait characteristics with a single accelerometer in the laboratory and community:

- a feasibility, validity and reliability study. *Journal of NeuroEngineering and Rehabilitation*. 2017;14(1):1-10.
45. Morris R, Stuart S, McBarron G, Mancini M, Fino PC, Curtze C. Validity of mobility lab (version 2) for gait assessment in young adults, older adults and Parkinson's disease. *Physiological Measurement*. 2019;40(9).
 46. Howell DR, Kirkwood MW, Provance A, Iverson GL, Meehan WP, 3rd. Using concurrent gait and cognitive assessments to identify impairments after concussion: a narrative review. *Concussion*. 2018;3(1).
 47. Mitchell CJ, Cronin J. Methodological critique of concussive and non-concussive dual task walking assessments: A scoping review. *International Journal Of Environmental Research And Public Health*. 2023;20(6):1-26.
 48. Dwan K, Li T, Altman DG, Elbourne D. CONSORT 2010 statement: Extension to randomised crossover trials. *British Medical Journal*. 2019;366:1-16.
 49. Horak F, King L, Mancini M. Role of body-worn movement monitor technology for balance and gait rehabilitation. *Physical Therapy*. 2015;95(3):461-70.
 50. Mobbs RJ, Perring J, Raj SM, Maharaj M, Yoong NKM, Sy LW, et al. Gait metrics analysis utilizing single-point inertial measurement units: A systematic review. *MHealth*. 2022;8:9.
 51. Gordt K, Gerhardy T, Najafi B, Schwenk M. Effects of wearable sensor-based balance and gait training on balance, gait, and functional performance in healthy and patient populations: A systematic review and meta-analysis of randomized controlled trials. *GERONTOLOGY*. 2018;64(1):74-89.
 52. Mariani B, Jimenez MC, Vingerhoets FJG, Aminian K. On-shoe wearable sensors for gait and turning assessment of patients with Parkinson's Disease. *IEEE Transactions on Biomedical Engineering*. 2013;60(1):155-8.
 53. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Medicine*. 2000;30(1):1-15.
 54. Hopkins WG. A new view of statistics 2015 [Available from: <https://www.sportsci.org/2015/ValidRely.htm>].
 55. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*. 2016;15(2):155-63.
 56. Uthoff A, Oliver J, Cronin J, Winwood P, Harrison C. Prescribing target running intensities for high-school athletes: Can forward and backward running performance be autoregulated? *Sports*. 2018;6(3):77-.
 57. Buchheit M, Mendez-Villanueva A. Reliability and stability of anthropometric and performance measures in highly-trained young soccer players: Effect of age and maturation. *Journal of Sports Sciences*. 2013;31(12):1332-43.

58. Turner A, Brazier J, Bishop C, Chavda S, Cree J, Read P. Data analysis for strength and conditioning coaches: Using Excel to analyze reliability, differences, and relationships. *Strength and Conditioning Journal*. 2015;37(1):76-83.
59. Howell DR, Osternig LR, Chou L-S. Consistency and cost of dual-task gait balance measure in healthy adolescents and young adults. *Gait & Posture*. 2016;49:176-80.

Appendices

Appendix A – Ethics Approval

3 March 2022

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **22/23 The reliability of a dual task walking protocol using Plantiga foot pod technology**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 3 March 2025.

Non-Standard Conditions of Approval

1. Please include an additional bullet point in the Consent Form with a yes/no option for participants to agree to have their data stored indefinitely and for future use.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the [Auckland University of Technology Code of Conduct for Research](#) and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.
8. AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through <http://www.aut.ac.nz/research/researchethics>

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: CourtneyMitch42@gmail.com

Appendix B - Participant Information Sheet

Date Information Sheet Produced:

21 January 2022

Project Title

The reliability of a dual task walking protocol using Plantiga foot pod technology.

An Invitation

Hello, my name is Courtney Mitchell, and I am a Master's student completing the Master of Sport, Exercise, and Health, delivered by Auckland University of Technology. I invite you to take part in an exciting research project. This study is called "The reliability of a dual task walking protocol using Plantiga foot pod technology." The aim of this study is to determine how consistently inertial sensors placed in an inner sole in your shoe can calculate variables like step length, step frequency etc. during a walking protocol where you are counting backwards. This information will benefit you by providing insight into your gait pattern and if there are any asymmetries between legs. We would be very grateful to you if you could participate in our study. Your participation is entirely voluntary, and you will not be disadvantaged by not participating.

What is the purpose of this research?

Concussions are an often misdiagnosed or underestimated mild brain injury, which can lead to further brain damage if a second concussion occurs as a result of a poor diagnosis. Current diagnostic protocols involve individuals performing a cognitive task, such as counting backwards in sevens from a given number, while walking to assess the effects of concussion. However, 3D motion capture and/or force plates are the most common technology used for this assessment, which is expensive, difficult to use, and involves a substantial period of time to analyse the data collected. The Plantiga foot pod technology offers the potential for a low-cost, user-friendly, high-utility technology to be used for a dual-task walking protocol that can assist with assessing concussion in a timely fashion. Therefore, the purpose of this research is to determine the reliability of a dual task walking test using the Plantiga foot pod technology in non-concussed participants. This data will provide us with the variability associated with the metrics calculated by the foot pods/inertial sensors placed in your shoes. This is the first step in terms of determining if this innovative technology can provide meaningful data. The findings of this research will contribute towards the completion of a Master's in Sport, Exercise, and Health, and may be used for academic publications and presentations.

How was I identified and why am I being invited to participate in this research?

You have been invited to participate in this research based on seeing the flyer advertising this research, posted in various common areas at Toi Ohomai Institute of Technology. To be included in this research, you are a non-concussed, non-rehabilitating individual who will not experience a change in gait status over the two-week testing period. You will be excluded from this research if you have recently been medical diagnosed as concussed or rehabilitating from an injury that would affect gait parameters.

How do I agree to participate in this research?

If you agree to participate in this research, please email me to confirm your participation. A consent form will be provided to you on confirmation of participation. Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

The research will take place at the sports laboratory at Te Pare a Ruahine Aquatic Centre at Toi Ohomai over a two-week period, involving three separate testing sessions. During each testing session, you will be required to perform a dual task walking test using the Plantiga foot pods/inertial sensors placed in the innersoles of your shoes (see Figure 1). This will involve walking over level ground for two minutes while counting backwards in sevens from a given number. You will complete this three times with 30 seconds between trials. The exact same testing protocol will be repeated over three testing occasions separated by seven days. Each session will only require 20 minutes of your time and can be completed in your normal daily attire. However, the same set of shoes needs to be used on each testing occasion.

Figure 1

Plantiga foot pods/inertial sensors



What are the discomforts and risks?

This testing will carry the same amount of discomfort and risk typically experienced in normal walking; therefore there are no discomforts or risks associated with the testing.

How will these discomforts and risks be alleviated?

All risks will be minimised by performing the dual task walking test over level ground, as well as identifying any potential hazards that may occur during the protocol.

What are the benefits?

As a participant, you will get to experience new foot pod/inertial sensor technology and its potential applications. Also, we will identify if you have any gait imbalances and report these to you should these be deemed problematic i.e., >15% asymmetries between limbs and you have requested to see the results of the testing. This research will also benefit myself as part of my Master's degree in Sport, Exercise, and Health.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation, and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

All data will be de-identified and aggregated. Any material that is published will be presented as mean values. The information obtained will remain confidential and secure from unauthorised individuals in a private passworded computer. De-identified data may be stored indefinitely on the SPRINZ database, used for future research, and shared with SPRINZ approved researchers without an additional consent. This information will only be used for research purposes.

What are the costs of participating in this research?

There are no costs to participating in this research except for travelling to and from the testing facility and your time. You will need to dedicate approximately 20 minutes per testing session.

What opportunity do I have to consider this invitation?

You will have four weeks to respond to this invitation. Within this period, feel free to email regarding any questions or concerns you may have.

Will I receive feedback on the results of this research?

If you would like to see the findings from this study, please indicate on the informed consent form.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Professor John Cronin, john.cronin@aut.ac.nz.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEK, *ethics@aut.ac.nz*, (+649) 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Courtney Mitchell, courtneymitch42@gmail.com

Project Supervisor Contact Details:

John Cronin, john.cronin@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on *3 March 2022*, AUTEK Reference number *22/23*.

Appendix C - Participant Consent Form

Project Title: The reliability of a dual task walking protocol using Plantiga foot pod technology

Project Supervisor: John Cronin

Researcher: Courtney Mitchell

- I have read and understood the information provided about this research project in the Information Sheet dated 21 January 2022.
- I have had an opportunity to ask questions and to have them answered.
- I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.
- I understand that if I withdraw from the study then I will be offered the choice between having any data or tissue that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- I am not suffering from concussion or any injury that would change my gait status over the two-week testing period
- I agree to take part in this research.
- I wish to receive a summary of the research findings (please tick one): Yes No
- I wish to receive a summary of my personal findings (please tick one): Yes No

Participant's signature:

.....

Participant's name:

.....

Participant's Contact Details (if appropriate):

.....

Date:

Approved by the Auckland University of Technology Ethics Committee on 3 March 2022, AUTEK Reference number 22/23

Note: The Participant should retain a copy of this form

Appendix D – Literature Review Abstract

Objective: To understand the methodological approaches taken by various research groups and determine the kinematic variables that could consistently and reliably differentiate between concussed and non-concussed individuals.

Methods: MEDLINE via PubMed, CINAHL Complete via EBSCO, EBSCOhost, SPORTDiscus, and Scopus were searched from inception until 31 December 2021, using key terms related to concussion, mild traumatic brain injury, gait, cognition and dual task. Studies that reported spatiotemporal kinematic outcomes were included. Data were extracted using a customised spreadsheet, including detailed information on participant characteristics, assessment protocols, equipment used, and outcomes.

Results: Twenty-three studies involving 1030 participants met the inclusion criteria. Ten outcome measures were reported across these articles. Some metrics such as gait velocity and stride length may be promising but are limited by the status of the current research; the majority of the reported variables were not sensitive enough across technologies to consistently differentiate between concussed and non-concussed individuals. Understanding variable sensitivity was made more difficult given the absence of any reporting of reliability of the protocols and variables in the respective studies.

Conclusion: Given the current status of the literature and the methodologies reviewed, there would seem little consensus on which gait parameters are best to determine return to play readiness after concussion. There is potential in this area for such technologies and protocols to be utilised as a tool for identifying and monitoring concussion; however, improving understanding of the variability and validity of technologies and protocols underpins the suggested directions of future research. Inertial measurement units appear to be the most promising technology in this aspect and should guide the focus of future research.

Impact: Results of this study may have an impact on what technology is chosen and may be utilised to assist with concussion diagnosis and return to play protocols.

Key Words: concussion, gait, locomotion, dual task

Appendix E – Reliability Article 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 utilised such as 3D motion capture and force plates are too complex and expensive for most practitioners.

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

Results: 3-4 participants were allocated to each randomised 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.

Funding: This research was funded by Movement Solutions, who had no involvement in the study design, collection, analysis, or writing of this report.