Spinal Cord (2021) 59:675–683
https://doi.org/10.1038/s41393-020-00559-4

ARTICLE

Using wearable sensors to characterize gait after spinal cord injury: evaluation of test–retest reliability and construct validity

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Received: 4 May 2020 / Revised: 18 September 2020 / Accepted: 21 September 2020 / Published online: 6 October 2020

Abstract

Study design Quantitative cross-sectional study.

Objectives Evaluate the test–retest reliability and the construct validity of inertial measurement units (IMU) to characterize spatiotemporal gait parameters in individuals with SCI.

Setting Two SCI rehabilitation centers in Canada.

Methods Eighteen individuals with SCI participated in two evaluation sessions spaced 2 weeks apart. Fifteen able-bodied individuals were also recruited. Participants walked 20 m overground under five conditions that challenged balance to varying degrees. Five IMU were attached to the lower-extremities and the sacrum to collect the mean and the coefficient of variation of five gait parameters (gait cycle time, double-support percentage, cadence, stride length, stride velocity). Intra-class correlation coefficients (ICC) were used to evaluate the test–retest reliability. Linear mixed-effects models were used to compare the five walking conditions to evaluate known-group validity while Spearman's correlation coefficients were used to characterize the level of association between gait parameters and the Mini BESTest (MBT).

Results Cadence was reliable across all walking conditions. Reliability was higher for the mean (ICC = 0.55–0.98) of the parameters compared to their coefficient of variation (ICC = 0.16–0.97). Cadence collected with IMU had construct validity as their values differed across walking conditions and groups of participants. The coefficient of variation was generally better than the mean to show differences across the five walking conditions. The MBT was moderately to strongly associated with mean cadence ($\rho \geq 0.498$) and its coefficient of variation ($\rho \leq -0.49$) during most walking conditions.

Conclusions IMU provide reliable and valid measurements of gait parameters in ambulatory individuals with SCI.

Introduction

Individuals with spinal cord injury (SCI) who are able to walk are at a high risk of falling; 78% of ambulators with SCI fall at least once each year [1]. This can lead to various consequences such as physical injuries and reduced social participation [2]. As the majority of these falls happen during walking and balance impairment is a significant contributor to having a fall [2], investigating balance ability during walking is needed to develop treatment strategies aimed at reducing the risk of falling among ambulatory individuals with SCI.

Following a SCI, walking characteristics adapt in part because of impaired balance ability. For example, ambulatory individuals with SCI will reduce their walking speed, increase the width of their base of support, decrease their step length, and increase the time spent in double support in order to compensate for their balance deficiencies [3, 4].

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They also exhibit increased variability of step length, step width, and foot placement in comparison to able-bodied individuals [5]. This has been associated with poorer performance on clinical assessments of balance and walking stability [5]. Balance can be further challenged in this population by altering the availability of sensory inputs [6] or by introducing a dual task [7], highlighting the fact that many contributors to balance control are affected following a SCI [8]. Hence, a comprehensive evaluation of gait for individuals with SCI should include measurement of these parameters and their variability during a variety of challenging walking conditions.

Wearable inertial measurement units (IMU), consisting of a three-dimensional (3D) accelerometer and a 3D gyroscope, provide accurate and sensitive measurement for gait analysis. Further, their ease of use, inexpensiveness and unobtrusiveness are an advantage for clinical evaluations of walking and balance over complex laboratory instruments [9, 10]. More importantly, their measured parameters possess criterion-validity and reliability in healthy adults [11] and have shown the potential to assess movement disorders [12, 13] and detect the incidence of falling in elderly individuals [14]. In fact, gait parameters such as stride length, double support time, and stance time are related to balance during walking, increased fall risk, and/or fear of falling in various populations such as Parkinson's disease and traumatic brain injury [9, 12].

Based on a recent systematic review on the evaluation of balance ability in individuals with SCI, IMU have not been used to characterize balance during walking in the SCI population [15]. Arora et al. formulated recommendations for balance assessment based on the clinical usefulness, comprehensiveness and psychometric properties of various instruments [15]. IMU may characterize the various components of balance [8], while possessing more clinical utility than laboratory assessments [9], although its psychometric properties in individuals with SCI have not been investigated. Therefore, the aim of this study was to evaluate the test–retest reliability of IMU as well as its construct validity in individuals with SCI. Two aspects of construct validity were evaluated. Known-group validity was explored by comparing spatiotemporal gait parameters derived from IMU of individuals with SCI and able-bodied individuals under different walking conditions that challenged balance to varying degrees (i.e., walking on foam, walking with reduced vision). Convergent validity was evaluated by looking at the association between these parameters and a clinical assessment of balance. We hypothesized that among ambulatory individuals with SCI, the gait parameters derived from IMU would have (1) good to excellent test–retest reliability (i.e., intra-class correlation coefficients (ICC) ≥ 0.75), (2) known-group validity, as evidenced by significant differences in gait parameters when normal walking was compared to walking under challenging conditions, significant differences between individuals with SCI and able-bodied individuals walking under these conditions, and (3) convergent validity, as evidenced by adequate association of these parameters with a clinical assessment of balance.

Material and methods

Participants and setting

A convenience sample of individuals with a traumatic or a non-traumatic SCI was recruited on a volunteer basis from the outpatient population of the CIUSSS du Centre-Sud-de-l'Île-de-Montréal (Installation Gingras-Lindsay) and the Lyndhurst Centre, Toronto Rehabilitation Institute-University Health Network. Inclusion criteria were as follows: (1) Adults with a motor incomplete (AIS C or D) SCI of traumatic and non-traumatic etiology (time since injury ≥ 5 months), (2) Ability to walk without assistive devices and human assistance for 6 min to ensure that intrinsic balance ability could be studied and that participants could complete all walking tests. Participants were excluded if they presented with another neurological disorder, significant visual deficits not corrected with glasses, and/or vestibular deficits. To explore more specifically known-group validity, 15 aged-matched able-bodied individuals were also recruited to participate in this study and compared to a subgroup of 15 individuals with SCI. Ethical approval was obtained from the institutions' research ethics boards. After reading and understanding the information about the research objectives and procedures, the participants gave their consent prior to initiating study activities. Demographic information about each participant's age, sex, and diagnosis were collected (Table 1). Based on preliminary data collected to address the first objective (i.e., evaluation of test–retest reliability), it was determined that a sample size between 12 and 18 participants was required depending on the gait parameter studied. To calculate the required sample size, estimated ICCs of 0.85–0.87 were used along with a 95% confidence interval [16].

Study procedures

Each participant with SCI attended two testing sessions spaced two weeks apart. Able-bodied participants attended only one testing session. One researcher per facility conducted the following walking tests with all participants. Participants walked straight for 20 m overground under 5 conditions that challenged balance to varying degrees during walking: (1) hard surface with full vision (NML), (2) hard surface with impaired vision (VISION), (3) foam with

Table 1 Descriptive characteristics of participants with a spinal cord injury ($n = 18$) and able-bodied participants ($n = 15$).

Clinical characteristics	Participants with SCI		Able-bodied participants
	Group ($n = 18$)	Subgroup ($n = 15$)	Subgroup ($n = 15$)
Age (years)	55.9 (20.6)	50.1 (17.1)	45.0 (17.6)
Height (cm)	172.6 (8.6)	173.5 (8.7)	170.2 (10.2)
Weight (kg)	79.6 (17.3)	82.1 (17.6)	72.6 (17.1)
Sex (male/female)	M: 14, F: 4	M: 13, F: 2	M: 7, F: 8
Time post lesion (months)	65.1 (65.7)	60.1 (65.1)	NA
LEMS (/50)	44.4 (4.0)	44.3 (4.2)	NA
MBT (/28)	21.0 (4.3)	21.5 (4.5)	NA
Level of lesion	P: 11, T: 7	P: 10, T: 5	NA
C1–C4	2	1	NA
C5–C8	6	5	NA
T1–T6	3	2	NA
T7–T12	5	5	NA
L1–L5	2	2	NA
AIS severity grade	18 (100%)	15 (100%)	NA
Type of lesion	TR: 13, NT 5	TR: 12, NT 3	NA

Values displayed in the table as mean (standard deviation) or number depending on the variable type. Except for the sex of participants, no significant differences existed between the subgroups on the various clinical characteristics. However compared to age, sex was not a significant predictor of IMU-derived gait parameters ($p \geq 0.09$).

SCI Spinal cord injury, *LEMS* Lower Extremity Motor Score, *MBT* Mini BESTest, *M* male, *F* female, *P* paraplegia, *T* tetraplegia, *TR* traumatic, *NT* non-traumatic, *NA* not applicable.

full vision (FOAM), (4) foam with impaired vision (VISION + FOAM), and (5) a dual-task condition that combined a cognitive task with walking (DUAL). Vision was impaired using safety goggles (3 M, London, Canada) with several layers of transparent vinyl (Kittrich, USA) attached to distort visual inputs. Foam pads of medium density and of 3 in. thickness (Velva 60, Domfoam, Canada) were secured to the participants' shoes using Velcro straps. Various foam thicknesses were tested empirically on able-bodied individuals and individuals with SCI prior to the study. Three inches was chosen since it sufficiently challenged balance, while minimizing tripping hazard. For the dual-task condition, patients were asked to name the months of the year backward in their first language (i.e., French or English), starting at a random month chosen by the researcher. For all walking conditions, participants walked without any assistive devices or human assistance. However, they could wear a lower limb orthosis, such as an ankle-foot orthosis, if needed. Participants began with the NML condition to become familiar with the testing procedures and equipment. The remaining four walking conditions were presented in a random order. Rest breaks were taken between trials as needed.

Outcome measures

Participants wore five IMU (GaitUp, Lausanne, Switzerland) to collect gait parameters during the walking conditions. IMU were attached on both feet (over metatarsals), both shanks (on the lower third of the tibia), and the sacrum [17]. Following the testing session, data were downloaded from the IMU using Physilog®5 Research ToolKit software and subsequently processed with custom-written programs (Matlab, Mathwork inc.). Five spatiotemporal parameters of gait were obtained for each gait cycle; namely the gait cycle time (GT, in seconds), the double-support percentage (DS, as a percentage of GT), the cadence (CA, in steps per minute), the stride length (SL, in meters), and the stride velocity (SV, as SL over GT in meters/second). These parameters were chosen based on previous studies indicating that they may be affected following SCI [18]. They are also potential biomarkers of dynamic equilibrium (GT and DS) and spatiotemporal coordination (SV, SL, and CA) in individuals presenting with neurological deficits [12]. For each gait cycle an average value, including values from both legs, was first calculated for these five parameters. Then, the data of the first and last three gait cycles were discarded to prevent gait initiation and termination from impacting the data. Subsequently, the mean and coefficient of variation over the total number of gait cycles during a given walking condition was calculated and served as the dependent variables in the statistical analyses. Previous studies have tested the accuracy of the IMU-derived gait parameters against a reference system, which would be valid for both the average and inter-stride variability.

Clinical test of balance and strength was also performed at the first testing session on individuals with SCI. The Mini Balance Evaluation Systems Test (MBT) is a clinical postural control scale encompassing 14 items, each rated on a three-level ordinal scale ranging from 0 (severe postural control impairment) to 2 (no postural control impairment), with a maximal score of 28 [19, 20]. The Lower Extremity Motor Score Assessment (LEMS), a clinical test of lower extremity strength, was conducted according to the International Standards for Neurological Classification of Spinal Cord Injury [21]. In this test, 5 major muscle groups are evaluated, representing the myotomes from L2 to S1, using a 6 point (0–5) ordinal scale.

Statistical analysis

Descriptive statistics (mean and SD) were used to report the demographic information of the participants (i.e., height, weight, sex, age, and time post injury), the gait parameters, the MBT, and the LEMS scores. Test–retest reliability was assessed using the ICC. According to Koo and Li [22], ICCs are considered poor under 0.5, moderate between 0.5 and 0.75, good between 0.75 and 0.9, and excellent when above 0.9. Subsequent analyses were conducted only on parameters possessing moderate to excellent test–retest reliability. The level of association between the MBT and the various walking conditions was explored using Spearman's correlation coefficients (ρ). Correlation coefficients were interpreted as good to strong when ≥0.70, moderate when between 0.4 and 0.6, and weak when below 0.4 [23]. Between conditions and group differences at the second testing session were explored on the subgroups of individuals with SCI and able-bodied individuals using a linear mixed-effects model. The normality of the data distributions was evaluated using the Shapiro–Wilk test and data transformation was then performed. Post-hoc pairwise comparisons were performed using estimated marginal means with the Tukey test. The effect sizes of these pairwise comparison were explored using Cohen's d and were interpreted as follow: 0.2 = small, 0.5 = medium, and 0.8 = large [24]. The second testing session was chosen rather than the first one, as participants with SCI were more familiar with the equipment and study procedures at the second testing session. Threshold for statistical significance was set at 0.05. All statistical tests were conducted on R version 3.3.3 [25].

Results

Participants' characteristics and descriptive clinical data

Eighteen individuals with SCI participated. See Table 1 for demographic and injury-related information.

Test-retest reliability

Table 2 reports the ICCs for the mean and CV of all five gait parameters during all five walking conditions. Overall CA showed the highest test–retest reliability among gait parameters since seven out of the ten ICCs generated for this parameter were considered excellent (ICC ≥ 0.91). Good to excellent reliability was also found for the means of the other parameters (ICC ≥ 0.78), with the exception of the mean DS percentage for the NML (ICC = 0.55), and VISION (ICC = 0.70) conditions, and mean of GT in the VISION + FOAM (ICC = 0.62) condition. The CV of GT, DS, and CA generated moderate to excellent levels of reliability (between 0.70 and 0.97) except for the NML walking condition (ICC ≤ 0.64) and the CV of DS in the VISION + FOAM condition (ICC = 0.70). With the exception of the CV of SV in the VISION condition, all CV of SL and SV displayed poor levels of reliability (ICC ≤ 0.50) for all walking conditions.

Correlation analysis

Table 3 displays the correlation coefficients between the MBT and the CA. The MBT was significantly and positively correlated with the mean CA for all walking conditions ($\rho \geq 0.498$, $p \leq 0.050$) and significantly and negatively correlated with the CV of CA for all conditions ($\rho \leq -0.49$, $p \leq 0.039$) except for the VISION condition ($\rho = -0.351$, $p = 0.167$).

Differences between groups and conditions

Figure 1 displays differences between the groups and the walking conditions for the mean and the coefficient of variation of CA. Significant between-groups ($p < 0.05$) and between-conditions ($p < 0.0001$) differences were observed for the mean and the coefficient of variation of CA. A significant interaction between groups and conditions existed only for the coefficient of variation of CA ($p = 0.01$).

Post-hoc analysis revealed that the mean of CA of individuals with SCI was significantly larger in NML than in DT, FOAM, and VISION + FOAM ($p \leq 0.007$, ES ≥ 0.72) (Fig. 1). The mean of CA of able-bodied individuals was significantly larger in VISION + FOAM than in VISION ($p = 0.005$, ES = 0.77) (Table 4).

The CV of CA was significantly lower in NML than in DUAL, FOAM, VISION, and VISION + FOAM ($p \leq 0.0045$, ES ≥ 1.23) for individuals with SCI. Lastly, a significant difference existed between individuals with SCI and able-bodied individuals on the VISION + FOAM condition ($p = 0.018$, ES = 1.47) (Table 5).

Discussion

Summary of findings

Individuals with SCI are at risk of falling when walking, with a reported pool incidence proportion of falls of 78% [1]. Since loss of balance is reported as being one of the main biological contributor to having a fall [1], a better understanding of how gait parameters can be affected when walking through various conditions is justified. To our knowledge, this is the first study to report the use of IMU to characterize walking in a SCI population. Our results showed support for the reliability and validity of IMU to assess the gait of individuals with SCI. This study also reveals that IMU-derived gait parameters can detect changes in gait stability in a group of high-functioning individuals with SCI.

Table 2 Test–retest reliability of the gait parameters, expressed with intra-class coefficient of correlation (ICC), for all walking conditions for individuals with SCI.

Gait parameter	Statistics	Walking condition				
		NML	DUAL	VISION	FOAM	VISION + FOAM
Gait cycle time (GT)	Mean	0.94	0.81	0.93	0.97	0.62
	CV	0.27	0.7	0.83	0.79	0.79
Double-support (DS)	Mean	0.55	0.78	0.7	0.89	0.79
	CV	0.38	0.83	0.72	0.88	0.7
Cadence (CA)	Mean	0.97	0.88	0.95	0.95	0.92
	CV	0.64	0.97	0.93	0.88	0.94
Stride length (SL)	Mean	0.96	0.9	0.97	0.89	0.93
	CV	0.38	0.26	0.5	0.3	0.18
Stride velocity (SV)	Mean	0.98	0.92	0.96	0.92	0.96
	CV	0.3	0.16	0.71	0.29	0.35

NML: walking on hard surface with normal vision, DUAL: walking on hard floor while naming months backward, VISION: walking on hard floor with goggles, FOAM: walking on foam with normal vision, VISION + FOAM: walking on foam with goggles, CV: coefficient of variation.

Table 3 Correlation coefficients between the Mini BESTest and the mean and coefficient of variation of gait cadence of all walking conditions for individuals with SCI.

Walking condition	Mean		CV	
	Coefficient	*P* value	Coefficient	*P* value
NML	0.518	0.033	−0.550	0.022
DUAL	0.798	0.000	−0.490	0.039
VISION + FOAM	0.498	0.050	−0.701	0.002
FOAM	0.603	0.008	−0.514	0.029
VISION	0.544	0.034	−0.351	0.167

NML: walking on hard surface with normal vision, DUAL: walking on hard surface with normal vision while performing a dual-task (naming months backward), VISION: walking on hard surface with goggles, FOAM: walking on foam with normal vision, VISION + FOAM: walking on foam with goggles.

Test–retest reliability of gait parameters derived from IMU in individuals with SCI

In general, the inter-stride mean value of gait parameters during 20-m walking trials showed a higher level of test–retest reliability compared to their inter-stride CV. This is supported by previous studies involving other clinical populations [26–28]. In fact, except for the mean of DS in the NML condition (0.55) and VISION condition (0.70) and the mean of GT in the VISION + FOAM condition (0.62), the level of reliability was considered good to excellent. In their systematic review, Yang et al. report good levels of reliability for the mean of various gait parameters in individuals with neurological disorders [28]. Beauchet et al. also reported that the reliability of GT was better during single-tasking vs. dual-tasking in older individuals with or without cognitive deficits, which was also observed in our study [26]. Our results are therefore in line with what has been previously reported.

At the same time, the CVs presented a lower level of reliability. Low levels of test–retest reliability for gait variability parameters have been reported for other populations presenting with neurological conditions [28]. Although the number of strides sampled is known to affect the reliability of gait variability, no definite consensus exists on the minimum number required to achieve an adequate level of reliability. For instance, Hollman et al. recommend that a minimum of 220 strides is necessary to reach an ICC of 0.9 for SV in healthy older individuals [27]. Some studies recommend between 30 and 50 strides to reliably evaluate various gait parameters in different populations [29, 30], while others stated that 12 strides may be sufficient [31]. Particularly, Lindemann et al. recommended 20 strides or more for calculation of the inter-stride variability of gait parameters [32]. Our participants walked over 20 m, which generated a number of strides similar to the latter value recommended. Our obtained ICC for the CV of GT, DS, and CA were considered good to excellent, except for those obtained in the NML walking condition. Hollman et al. state that collecting data on an heterogenous population such as those with a neurological disease may lead to more reliable variability data, which may explain our results [27]. Therefore, our results indicate that the distance selected in our protocol was sufficient to reach a moderate level of test–retest reliability for the CV of CA in individuals with SCI although a greater distance may have improved the reliability of other parameters. At the same time, measurement of hundreds of strides during the five conditions in our study could lead to an onset of fatigue in the individuals with SCI that could negatively affect the measured inter-stride repeatability.

As stated previously, the test–retest reliability was lower for the CV of SL and SV, as well as in the NML walking condition. It is unclear at the present time what may be

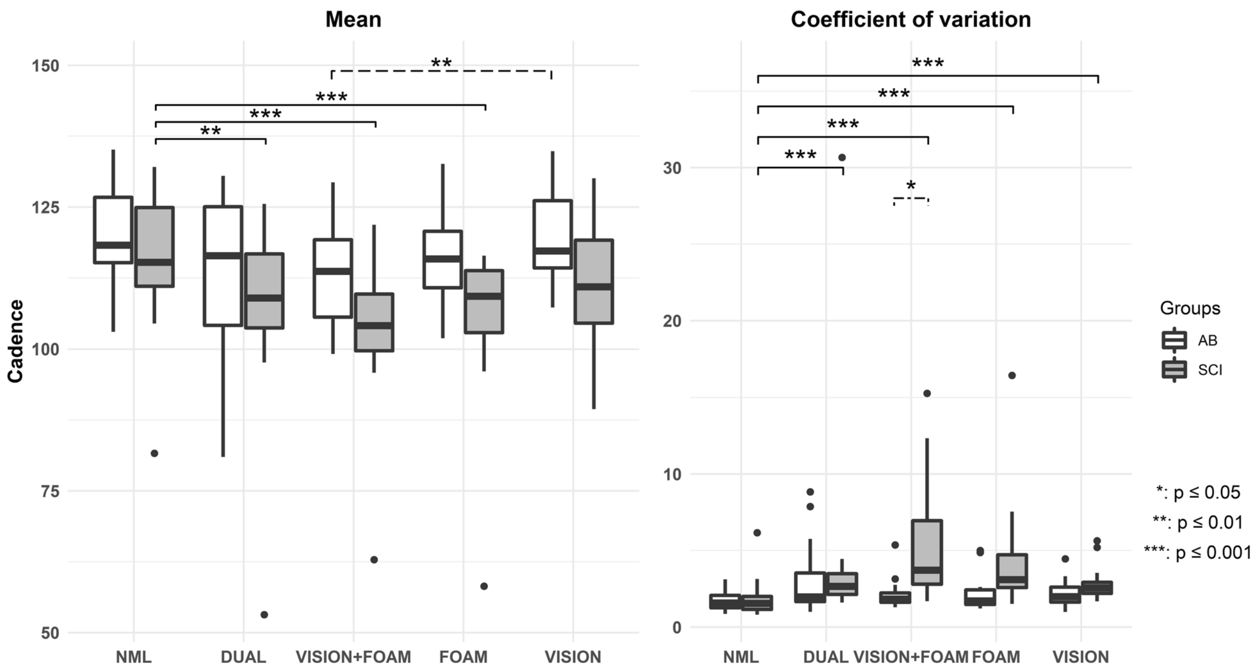

Fig. 1 Boxplot of the mean and inter-stride coefficient of variation of cadence in various walking conditions for individuals with SCI and able-bodied individuals. Participants underwent the following walking trials: (1) walking on hard surface with normal vision (NML), (2) walking on hard surface with normal vision while performing a dual-task, i.e., naming months backward (DUAL), (3) walking on hard surface with blurred goggles (VISION), (4) walking on foam with normal vision (FOAM), and (5) walking on foam with blurred goggles (VISION + FOAM). Significant differences were indicated with $*p \leq 0.05$, $**p \leq 0.01$, and $***p \leq 0.001$.

Table 4 Effect sizes for the post-hoc contrasts for the mean and coefficient of variation of cadence for individuals with SCI.

Contrasts	SCI		AB	
	Mean	CV	Mean	CV
NML~DUAL	**0.72**	**1.23**	0.45	0.72
NML~ VISION + FOAM	**1.08**	**1.66**	0.69	0.67
NML~FOAM	**0.95**	**1.39**	0.42	0.51
NML~VISION	0.43	**1.24**	0.03	0.61
DUAL~ VISION + FOAM	0.43	0.55	0.18	0.28
DUAL~FOAM	0.23	0.21	0.08	0.33
DUAL~VISION	0.30	0.17	0.51	0.25
VISION + FOAM ~FOAM	0.24	0.33	0.30	0.11
VISION + FOAM ~VISION	0.70	0.79	**0.77**	0.01
FOAM~VISION	0.53	0.40	0.49	0.10

Values in bold are statistically significant. NML: walking on hard surface with normal vision, DUAL: walking on hard floor while naming months backward, VISION: walking on hard floor with goggles, FOAM: walking on foam with normal vision, VISION + FOAM: walking on foam with goggles.

SCI spinal cord injury, *AB* able-bodied.

Table 5 Effect sizes for the post-hoc contrasts comparing able-bodied individuals to individuals with SCI for the mean and coefficients of variation of cadence.

Condition	SCI-AB contrast	
	Mean	CV
NML	0.28	0.00
DUAL	0.57	0.41
VISION + FOAM	0.90	**1.47**
FOAM	1.05	1.11
VISION	0.83	0.82

Values in bold are statistically significant. NML: walking on hard surface with normal vision, DUAL: walking on hard floor while naming months backward, VISION: walking on hard floor with goggles, FOAM: walking on foam with normal vision, VISION + FOAM: walking on foam with goggles.

SCI spinal cord injury, *AB* able-bodied.

responsible for this low reliability. We cannot rule out the impact of beginning our evaluation session with the NML walking condition without any prior familiarization session. It is possible that how the participant performs during that first walking condition (NML) will vary more between sessions than the following conditions, which resulted into a lower level of reliability.

Construct validity of gait parameters in individuals with SCI

The second aim of our experiment was to assess the construct validity of IMU-derived gait parameters to assess post-SCI gait. To this end, the inter-stride mean and CV of CA were used to explore performance of individuals with

SCI under various walking conditions and compare it to that of able-bodied individuals. Previous studies have reported that gait variability measures (e.g., CV of gait parameters) were associated with balance during gait and the risk of falling in various populations [13, 33]. Results of our study are in line with these studies since moderate to excellent levels of association were found between gait variability parameters and the MBT.

Gait variability is also reported to be more sensitive than the inter-stride mean value of gait parameters to characterize gait stability of older populations [31]. Higher variability in gait parameters can indicate that more attention is involved [26]. Therefore, by introducing elements that can modify the somatosensory inputs or the level of attention, we expected that gait variability measures (i.e., CV of gait parameters) would be more affected than the mean values. This was supported by our observations since the CV parameters were more powerful than the mean parameters in discriminating these walking conditions in individuals with SCI as indicated by the fact that most effect sizes were higher for the CV parameters than for the mean for a given contrast between two conditions (Table 4). Therefore, our results support the relevance of gait variability measures for gait stability analysis of individuals with SCI.

Manipulating sensory information challenges the balance system. In fact, according to our observations, the VISION + FOAM condition was the most challenging walking condition, with generally higher CV of most gait parameters than other conditions (Fig. 1). Interestingly, a difference in performance between individuals with SCI and able-bodied individuals was only found for the CV of CA during the VISION + FOAM condition, although an overall group difference was found for the mean and CV of CA. Altogether, these findings can guide clinicians when selecting progressively difficult exercises namely based on sensory integration when working on balance during walking in individuals with SCI.

Selection of gait parameters

Various gait parameters can be derived from IMUs and our study indicates that CA possesses good test–retest reliability and construct validity following SCI. According to Horak et al., CA is a meaningful parameter to characterize the spatiotemporal coordination of gait [12]. Variability of GT can be used as a biomarker for dynamic balance in individuals with Parkinson's disease, while DS was shown as a biomarker of dynamic balance for the same population. Individuals with SCI also tend to have an increased DS [4, 12]. However, the present study revealed that the CV of GT and DS possesses moderate to good reliability only for the most challenging walking conditions which may limit their use to explore how balance is maintained in normal walking condition.

Limitations

This study possesses a number of limitations. First, the literature suggests that a potential confounding factor when interpreting the CV is gait velocity since gait variability may increase as velocity decreases [34]. In fact, our results show that mean SV was higher during the NML condition compared to the VISION + FOAM condition and the FOAM condition, i.e., walking on a compliant surface slowed down our participants. This may in part explain why the CV of gait parameters was higher during the latter conditions. Second, Rennie et al. used another approach to characterize gait variability that takes into account inter-stride (step-to-step) variability and the asymmetry between the right and left steps [30]. In a SCI population, asymmetry is often present during gait and so the interpretation of our results may be hindered by the methodology we have used. Moreover, to be included in this study, participants had to be able to walk without an assistive device and human assistance for 6 min. For this reason, most of these participants were high functioning as depicted by the mean spatiotemporal parameters reported here compared to previous studies. For instance, Fig. 1 reveals that the mean CA for the NML condition was around 115 step/min compared to mean values between 78.9 and 88.6 for individuals with paraplegia and tetraplegia, 104.1–109.1 reported for individuals with cervical spondylotic myelopathy [35], 75.07 for individuals with central-cord syndrome [36], and 70.58 for individuals with Brown-Séquard syndrome [36]. Therefore, the generalizability of the results is limited. Lastly, balance is known to be affected by spasticity, which was not evaluated in this study [37]. Future studies should explore criterion and concurrent validity of IMU in a SCI population as well as the relationship of IMU-derived gait parameters and the risk of falling in that population.

Conclusion

Cadence measured using IMU possesses moderate to excellent test–retest reliability and construct validity for evaluating walking through various conditions in individuals with SCI. The inter-stride variability of cadence was useful to characterize how balance was challenged during each walking condition. Those walking conditions that alter the somatosensory and visual inputs, alone or in combination, are likely to challenge the balance system in individuals with SCI.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Funding JFL was supported by a postdoctoral fellowship grant from the Craig H. Nielsen Foundation, Rick Hansen Institute. AN was supported by Alberta Innovates Graduate Student Scholarship. JU was supported by an Ontario Graduate Scholarship. HR was supported by Canadian Academy of Sports and Exercise Medicine, New Frontiers in Research Fund—Exploration, Alberta Ministry of Economic Development and Trade, Major Innovation Fund, NSERC & Alberta Innovates, Engage-CASBE, American Orthotics and Prosthetics Association Back/Spinal Bracing, IC Impact, Canadian India SCI Innovation Award, AIHS Alberta Innovates – PFIZER, Occupational Health and Safety (OHS) Futures, Research Funding Program, Glenrose Rehabilitation Hospital (Clinical Research Grant, Research and Development Grant), Natural Sciences and Engineering Research Council of Canada (NSERC) (Engage grant, Connect grant, Discovery grant, RTI grant), Faculty of Engineering, University of Alberta (Start-up Grant). KEM was supported by Canadian Institutes of Health Research, Craig H. Nielsen Foundation, Rick Hansen Institute, Ontario Neurotrauma Foundation, Heart and Stroke Foundation, US Department of Defense.

Author contributions JFL: Research project—conception, organization, execution; Statistical analysis—design, execution, review and critique; Manuscript—writing of the first draft. AN: Research project—execution; Statistical analysis—design, execution, review and critique; Manuscript—review and critique. JU: Research project—execution; Manuscript—review and critique. DJH: Research project—execution; Manuscript—review and critique. HR: Research project—conception, organization, execution; Statistical analysis—design, execution, review and critique; Manuscript—review and critique; KEM: Research project—conception, organization, execution; Statistical analysis—design, execution, review and critique; Manuscript—review and critique.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

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