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Reliability of Nonlinear Kinematic Analysis in Patients with Functional Ankle Instability During Dual-Task Walking

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SUMMARY

Objective. This study aimed to determine the intrasession reliability of nonlinear gait kinematic analysis under single and dual-task conditions in individuals with and without Functional ankle instability (FAI).

Methods. Individuals with FAI and healthy subjects completed a walking task on a treadmill, with or without performing an auditory Stroop task. The gait kinematic parameters, including the LyE of hip, knee, and ankle angles in three planes, were recorded. Cognitive task performance was analyzed using error ratio and average reaction time. The intraclass correlation coefficient (ICC) was utilized to determine the intrasession reliability of kinematic and cognitive outcome measures.

Results. ICCs for the FAI group in dual and single-task conditions ranged between 0.53 to 0.85 and 0.62 to 0.96, respectively. ICCs for healthy groups in dual and single-task conditions ranged between 0.47 to 0.89 and 0.86 to 0.95, respectively. Lower ICC values were mainly related to the hip and knee transverse planes ranging from 0.47 to 0.68. ICC values of the auditory Stroop task were higher in the reaction time variable (FAI (0.95), control (0.84)) than in the error ratio (FAI (-0.01), control (0.43)).

Conclusions. LyE of gait kinematics had moderate to very high reliability in participants with and without FAI in both single and dual-task conditions, and it might be helpful for clinical evaluation. The low intrasession reliability in hip and knee transverse planes must be interpreted cautiously.

KEY WORDS

Functional ankle instability; dual-task; gait; reliability; Lyapunov exponent; motion analysis; kinematics.

INTRODUCTION

Functional ankle instability (FAI) is one of the most prevalent musculoskeletal ailments, closely followed by lateral ankle sprains (1). Although individuals with FAI exhibit no signs of ligament laxity, they experience impaired function and recurrent ankle sprains due to their ankles frequently giving way (2). Proprioceptive impairment, weakness deficiencies, poor muscle recruitment, decreased ankle range of motion, and altered neuromuscular function may influence postural control and gait patterns in individuals with FAI (3-8).

Individuals with FAI have altered gait patterns during functional tasks, such as walking, which is the most common task in daily activities (9). Gait analysis under single-task conditions may restrict the validity of research and conceal changes in movement patterns under demanding situations (10). The effect of FAI on gait stability has been examined in relation to the dual task explained by performing two tasks concurrently. In managing posture and walking, cognitive factors play a crucial role. However, a literature study reveals that the role of cognitive factors in walking is typically neglected (11). According to research on several populations with balance issues, gait stability may be compromised during dual-tasking, diminishing balance control while walking. Thus, the dual-task paradigm can detect gait deficits that would otherwise remain hidden during normal walking (12, 13). In addition, since a behavior consists of three components - cognition, emotions, and executive functions - and sufficient evidence exists for the role of cognition in the central processing of information, dysfunction of executive functions, which is one of the components of behavior, can directly affect cognitive functions (14). Therefore, patients with FAI with difficulty in executive functions such as postural control should not be surprised to see cognitive impairments such as inattention. Siu *et al.* revealed that the performance of a cognitive task in the form of verbal reaction time declined as the difficulty level of the gait rose (15). Such research may imply that environmental degradation may influence the functionality of the central information processing system, even if it does not cause structural damage to information processing centers.

Even though human gait is a cyclic action, there is always a degree of variation in irregular fluctuations throughout time. Although linear statistics such as standard deviation and coefficient of variation are widely used to explain gait variability and estimate its magnitude, evidence has challenged the idea of linear dynamics (16, 17). This viewpoint is limited in disregarding the hidden temporal structure within the signal, which does not allow for a conclusive assessment of the dynamic features of the balancing control system. Examining the system's behavior over an extended period offers more accurate information. In contrast, the temporal pattern of gait variability or how gait evolves is crucial in measures derived from nonlinear statistics, indicating the interplay between the various locomotor and balance control system components (18). Using both types of linear and nonlinear analysis may be necessary to fully understand the behavior of a complex dynamical system, obtain a better interpretation of the characteristics of the locomotor system, and reach a more comprehensive result. The Lyapunov exponent (LyE) was employed to explore the present study's nonlinear dynamic behavior of postural oscillation. This technique examines gait stability and the dynamic system's susceptibility to disturbances (10, 19).

The intrinsic variability in gait patterns can affect the reliability and validity of kinematic outcomes. One of the criteria for choosing a parameter for evaluation, treatment, and biomechanical issues is its reliability. Reliability tells us how much relative error the test has in measurement. Although studies have investigated the reliability of gait kinematics measured with linear tools on healthy and clinical populations (20-23), little attention has been paid to the reliability of the nonlinear analysis. It is necessary to establish the reliability of LyE in various musculoskeletal disorders, including FAI, and in different experimental conditions, especially with a cognitive task. The cognitive-motor dual-task situation seems to increase the complexity of the task and extract more accurate information regarding gait kinematics than normal walking.

To the author's best knowledge, no study has been conducted to examine the reliability of the LyE of the hip, knee, and ankle angles in sagittal, frontal, and transverse planes in FAI. Since the lower extremity is a kinetic chain and functions as a unit, anything that affects the ankle is thought to affect the knee and hip as well. Additionally, in people with FAI, the fibula in the sprained ankle is positioned more anteriorly than the contralateral ankle, which may lead to rotary instability in the talocrural joint (24, 25). This finding suggests that researchers should pay attention to sagittal and transverse plane motions in FAI. Therefore, this study investigated the reliability of the LyE of the hip, knee, and ankle angles in three planes under single and dual-task walking in FAI and healthy adults. We hypothesized that the reliability of the LyE for lower limb kinematics would be acceptable under single and dual-task walking.

MATERIALS AND METHODS

Participants

Ethical approval was obtained from the Institutional Ethics Committee of Shahid Beheshti University (IR.SBMU.RETECH.REC.1400118 – Date of approval: June 18, 2021). Ten patients suffering from FAI (10 males) and ten healthy individuals (10 males) aged 18 to 40 participated in the study and signed the written consent form to participate in the research.

Participants in the FAI group had at least one significant ankle sprain occurring over the last 12 months that required protected weight-bearing for at least three days resulting in pain, swelling, and at least two episodes of "ankle giving way" in the past year. They were identified in the study using a Functional Ankle Ability Measure (FAAM) questionnaire to evaluate their performance, including the subscale of activities of daily living (ADL) and sports. They were excluded if they scored > 90% in the FAAM ADL score or > 80% in the FAAM sports score. Inclusion criteria for healthy subjects were free from a history of lateral ankle sprains. Both groups were free from visual and hearing disorders, dizziness, pain, and lower extremity surgery within the last six months before testing.

Procedure

The gait data on a treadmill was recorded by a 3D motion-capture system (Vicon Motion System Ltd®, Oxford, UK) with eight cameras placed at the height of 270 cm from the ground. The frame rate was also set to 100 Hz. Thirty-eight markers were attached to bony landmarks based on the Cluster algorithm. The markers were bilaterally attached to the superior anterior iliac spine, superior posterior iliac spine, femoral condyles of knee joints, malleoli, head area of the second metatarsus, the base area of the five metatarsi, the most prominent part of the heel area, and ten markers called cluster markers (4 markers in corner and one marker in the center) in the lower third and outside of the shank and the outer half of the thigh.

The experiment involved the immediate test-retest reliability accomplished in one day. The tested ankle of healthy subjects was defined by matching their leg dominance to the involved ankle of the FAI subjects. For example, if the injured ankle of the FAI subject was a non-dominant limb, the non-dominant limb of the healthy subject was determined for evaluation. The leg used for kicking a ball was defined as the dominant leg (26). All participants were familiarized with the testing procedure that contained barefoot treadmill walking at a self-selected speed. It lasted 6 minutes to ensure that subjects had similar gait patterns with over-ground walking (17). The reason for using the treadmill for walking is that a large amount of continuous data (*i.e.*, long time series) is needed to calculate the LyE. The participants walked on a treadmill for 95 seconds and completed two randomized conditions (three trials per condition), including 1) normal walking and 2) normal walking while performing a cognitive task.

In a dual-task condition, individuals were trained to pay enough attention to both walking and auditory Stroop task to avoid the effect of the task's priority. The auditory Stroop task is a modified version of the Stroop task usually used in the dual-task paradigm. The test was carried out in which two words, "high" and "low," were spoken in either high or low pitch. In the original auditory Stroop task (15), the respondents were asked to name the pitch of the sound. However, in the present study, the participants were instructed to recognize the pitch of the sound independent from the spoken word, reverse the answer, and say it as quickly as possible to increase the cognitive task difficulty. The stimulus was heard through a wireless headset (Rapoo, VH150). The auditory Stroop task was implemented using a custom program written in MATLAB (MATLAB R2021a) and was synchronized with the Vicon Motion System so that auditory signals played as soon as the participants started walking.

The LyE of the hip, knee, and ankle angles in three planes was used to measure gait kinematics. Error ratio (number of incorrect responses divided by the total number of stimuli) and average reaction time (the time required to respond to each auditory signal) were also used as two separate variables to measure cognitive performance.

Data processing

3D angles of lower limb joints have been extracted by a Cardan XYZ (flexion/extension-lateral bend-axial twist) rotation sequence. The flexion/extension angles were selected in this study for further analysis. The Cardan rotation sequence XYZ involves three steps: first, rotation about the laterally directed axis (X (flexion/extension)); second, rotation about the anteriorly directed axis (Y (lateral bend)); and third, rotation about the vertical axis (Z (axial twist)). After LCS (Local Coordinate System) computation for each segment, the resulting orientation matrix was used for extracting 3D angles. The angles for the XYZ sequence are designated α (alpha) for the first rotation, β (beta) for the second rotation, and ϒ (gamma) for the third rotation. The rotation matrix R and α angle for an XYZ rotation sequence are as follows:

$$R = \begin{bmatrix} \cos\gamma\cos\beta & \cos\gamma\sin\beta\sin\alpha + \sin\gamma\cos\alpha & \sin\gamma\sin\alpha - \cos\gamma\sin\beta\cos\alpha \\ -\sin\gamma\cos\beta & \cos\alpha\cos\gamma - \sin\gamma\sin\beta\sin\alpha & \sin\gamma\sin\beta\cos\alpha + \cos\gamma\sin\alpha \\ \sin\beta & \cos\beta\sin\alpha & \cos\beta\cos\alpha \end{bmatrix}$$

$$\alpha = \tan^{-1}\left(\frac{-R_{32}}{R_{33}}\right)$$

The LyE was calculated using the custom code in MATLAB software to examine joint angles in three planes. The LyE quantifies the separation rate of infinitesimally close trajectories. The LyE for sagittal angular hip, knee, and ankle angles displacement of time series was calculated using the algorithm presented by Wolf *et al.* (27). The LyE is zero for periodic data where there is no divergence in the trajectories. In other words, the trajectories overlap rather than diverge in the phase space. Five embedded dimensions were found for the present calculation. The LyE is relatively large for random noise when trajectories in the phase space have considerable divergence. We did not filter the joint kinematics to have a precise image of the variability during mentioned trials.

Statistical analysis

All calculations were performed using SPSS 26. Descriptive data were used to report the demographic characteristics. A two-way random model of intraclass correlation coefficient (ICC) was used to analyze the relative reliability of intrasession. For each ICC, a 95% confidence interval (CI) was reported to highlight the estimates' accuracy and to account for variance among the subjects. The relative reliability was classified based on Munro's classification. Munro determined the degrees of relative reliability based on ICC values: 0 to 0.25 little, 0.26 to 0.49 low, 0.50 to 0.69 moderate, 0.70 to 0.89 high, and 0.90 to 100 very high correlation (26).

For assessing absolute reliability, the standard error of measurement (SEM) was estimated as the square root of the mean square error term extracted from variance analysis. The minimal metrically detectable change (MMDC) was utilized to evaluate changes caused by error measurements and calculated as 95%CI of SEM of kinematic variables (SEM*1.96) (28).

RESULTS

There are no statistical differences based on demographic characteristics between groups ($p \geq 0.05$) (**table I**). Intrasession reliability results included the values of ICC, a 95%CI, SEM, and MMDC of the ankle, knee, and hip joints in three planes for two groups presented in **tables II**, **III**, and **IV**, respectively.

Table I. Demographic characteristics of participants with FAI and healthy controls.

Variables	FAI (n = 10)		Healthy (n = 10)		P-value
	Mean	SD	Mean	SD	
Age (year)	24.80	4.23	26.10	4.90	0.272
Body mass index (kg/m2)	24.59	5.31	26.47	3.60	0.333
Sports activity level*	2.00	0.66	1.90	0.73	0.865

P-values refer to the statistical significance of the chi-square test. SD: standard deviation; FAI: Functional Ankle Instability; *1: beginner; 2: semiprofessional; 3: professional.

Table II. Intrasession reliability of ankle Lyapunov exponent (LyE) during the single task and dual-task conditions in participants with FAI and healthy controls.

Conditions	Variables	Healthy					FAI				
		ICC	SEM	MMDC	95%CI for ICC		ICC	SEM	MMDC	95%CI for ICC	
					Lower	Upper				Lower	Upper
Single-task	AnkleX	0.91	0.06	0.16	0.78	0.97	0.92	0.05	0.16	0.79	0.97
Single-task	AnkleY	0.91	0.07	0.20	0.76	0.97	0.75	0.06	0.19	0.45	0.92
Single-task	AnkleZ	0.90	0.07	0.20	0.76	0.97	**0.62**	0.08	0.24	0.26	0.87
Dual-task	AnkleX	0.79	0.11	0.30	0.52	0.93	0.81	0.08	0.24	0.55	0.94
Dual-task	AnkleY	0.90	0.07	0.21	0.74	0.97	0.85	0.07	0.21	0.63	0.95
Dual-task	AnkleZ	0.90	0.07	0.21	0.75	0.97	0.84	0.07	0.21	0.62	0.95

X: Sagittal plane (dorsiflexion-plantarflexion); Y: Frontal plane (inversion, eversion); Z: Transverse plane (abduction, adduction); FAI: Functional Ankle Instability; ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; MMDC: Minimal Metrically Detectable Change; CI: Confidence Interval; highlighted values show ICC < 0.7.

Table III. Intrasession reliability of knee Lyapunov exponent (LyE) during the single task and dual-task conditions in participants with FAI and healthy controls.

Conditions	Variables	Healthy					FAI				
		ICC	SEM	MMDC	95%CI for ICC		ICC	SEM	MMDC	95%CI for ICC	
					Lower	Upper				Lower	Upper
Single-task	KneeX	0.87	0.08	0.22	0.68	0.96	0.79	0.08	0.22	0.52	0.93
Single-task	KneeY	0.92	0.05	0.15	0.78	0.97	0.92	0.07	0.19	0.79	0.97
Single-task	KneeZ	0.94	0.04	0.12	0.84	0.98	0.84	0.11	0.31	0.61	0.95
Dual-task	KneeX	0.89	0.08	0.22	0.73	0.97	0.74	0.09	0.27	0.44	0.92
Dual-task	KneeY	0.81	0.10	0.28	0.55	0.94	0.77	0.11	0.30	0.48	0.93
Dual-task	KneeZ	**0.68**	0.26	0.72	0.34	0.90	**0.53**	0.25	0.70	0.14	0.83

X: Sagittal plane (flexion-extension); Y: Frontal plane (abduction, adduction); Z: Transverse plane (internal rotation, external rotation); FAI: Functional Ankle Instability; ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; MMDC: Minimal Metrically Detectable Change; CI: Confidence Interval; highlighted values show ICC < 0.7.

Table IV. Intrasession reliability of hip Lyapunov exponent (LyE) during the single task and dual-task conditions in participants with FAI and healthy controls.

Conditions	Variables	Healthy					FAI				
		ICC	SEM	MMDC	95%CI for ICC		ICC	SEM	MMDC	95%CI for ICC	
					Lower	Upper				Lower	Upper
Single-task	HipX	0.86	0.07	0.20	0.66	0.96	**0.63**	0.09	0.25	0.27	0.88
Single-task	HipY	0.95	0.05	0.14	0.86	0.98	0.87	0.04	0.12	0.67	0.96
Single-task	HipZ	0.90	0.05	0.14	0.74	0.97	0.96	0.08	0.22	0.91	0.99
Dual-task	HipX	0.83	0.10	0.29	0.60	0.95	0.74	0.08	0.24	0.43	0.92
Dual-task	HipY	0.86	0.11	0.30	0.66	0.96	**0.58**	0.05	0.15	0.20	0.85
Dual-task	HipZ	**0.47**	0.18	0.51	0.07	0.80	**0.61**	0.29	0.82	0.24	0.87

X: Sagittal plane (flexion-extension); Y: Frontal plane (abduction, adduction); Z: Transverse plane (internal rotation, external rotation); FAI: Functional Ankle Instability; ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; MMDC: Minimal Metrically Detectable Change; CI: Confidence Interval; highlighted values show ICC < 0.7.

Kinematic variables

In examining the reliability of the two groups, different values were obtained according to the test's conditions. For ankle joints, healthy individuals in both single and dual-task conditions at three planes had high and very high ICC values ranging from 0.79 to 0.91, respectively. FAI group had the same ICC values in both single and dual-task (0.75-0.92), except for the LyE in the transverse plane during the cognitive task with a moderate ICC value of 0.62.

Knee joints in healthy participants showed high and very high values in ICC in a single task ranging from 0.87 to 0.94. For the dual task, the LyE in the transverse plane had a moderate ICC value of 0.68, but the other two kinematic planes indicated high reliability (0.81 and 0.89). In the FAI group, all individuals in both walking conditions had high and very high ICC values ranging between 0.74 and 0.92, except for the LyE in the frontal plane with a cognitive task that showed moderate ICC values of 0.53.

For hip joints, healthy participants indicated high and very high ICC values in both conditions ranging from 0.83 to 0.95, except for the LyE in the transverse plane with dual-task, which had a low ICC value of 0.47. People with FAI showed moderate ICC values in the sagittal plane (0.63), high and very high values in the frontal plane, and transverse plane in a single task, respectively (0.87 and 0.96). For dual-task, the ICC value in the sagittal plane was high (0.74), and in the frontal plane (0.58) and transverse plane (0.61) were moderate.

In general, ICC values of 5 out of 18 (27%) variables were lower than 0.70 in individuals with FAI. In the healthy group, these values were 2 out of 18 (11%). In healthy individuals, ICC values in single-task conditions ranged from 0.86 to 0.95, and in dual-task conditions ranged from 0.47 to 0.89. The ICC values for people with FAI in single-task ranged from 0.62 to 0.96, and in dual-task ranged from 0.53 to 0.85.

Cognitive task variables

The reliability of the two variables of the cognitive task is shown in **table V**. The ICC values for average reaction time in healthy and FAI groups were 0.84 and 0.95, respectively. The ICC values for the error ratio in healthy and FAI groups were 0.43 and -0.01, respectively. Negative ICC values indicated poor reliability due to the highly variable data for the error ratio.

Table V. Intrasession reliability of error ratio and averaged reaction time during the dual-task condition in participants with FAI and healthy controls.

Variables	Healthy					FAI				
	ICC	SEM	MMDC	95%CI for ICC		ICC	SEM	MMDC	95%CI for ICC	
				Lower	Upper				Lower	Upper
Error ratio	**0.43**	8.10	22.47	0.03	0.78	**-0.01**	5.39	14.95	-0.29	0.45
Average reaction time	0.84	0.01	0.03	0.61	0.95	0.95	0.01	0.03	0.87	0.98

FAI: Functional Ankle Instability; ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement; MMDC: Minimal Metrically Detectable Change; CI: Confidence Interval; highlighted values show ICC < 0.7.

DISCUSSION

Conducting research on reliability is a valuable method to ensure that measurement error is lower than the treatment effect. In other words, the higher correlation among different trials to examine the reliability can minimize the risk of type II error, thereby increasing the power of variable measures (26). In the present study, intrasession relative reliability in the FAI group was high to very high in 13 out of 18 variables. We found five variables with moderate ICC values, three under dual-task conditions. We also discovered that 16 out of 18 variables in healthy subjects demonstrated high to very high relative reliability. Two variables with low and moderate ICC values were when the dual-task was applied. The ICCs in dual-task walking - while slightly lower than the ICCs in normal walking, probably due to greater task complexity - represent moderate to very high reliability. Regardless of the effect of cognitive load, intrasession reliability in healthy subjects was generally higher than in subjects with FAI. In agreement with this result, previous studies have shown gait variability to be less reliable in people with postural instability (29) and dementia (30) compared to healthy individuals. Gait impairments and fluctuation of motor performance may result in less reliable estimates of gait variability.

The results of absolute reliability based on kinematic measures agree with the results of the relative reliability of intrasession, in which the higher the SEM, the lower the reliability of the test and the less precision in measurement. The cognitive perturbations can provoke gait dynamics, so SEM and MMDC values were generally higher across dual-task conditions. In contrast, Hamacher's investigation revealed that the reliability of the trunk parameter LyE was similar during normal treadmill walking and walking while texting (10). The differences in ICC values might result from different walking tasks analyzed. The study of Hamacher *et al*. (10) analyzed walking with a predetermined walking speed, whereas we analyzed gait kinematics with a preferred walking speed.

Based on the results, the variability in an individual's walking pattern is mainly reflected in the transverse plane motions. While applying a cognitive task could not affect the reliability of LyE in the ankle joint, the LyE of hip and knee joints in both groups in the transverse plane had lower reliability in dual-task than in other planes. This finding is consistent with a systematic review by McGinley *et al*. It is not surprising as the lowest reliability and highest error frequently occurred in the hip and knee transverse planes (< 0.60) due to the limited range of movement (28). Specifically, McGinley *et al*. identified hip rotation angles susceptible to the highest error. The small ranges of movement in the plane angles can compromise the signal-to-noise ratios of these angles and, thus, compromise their reliability (31). In agreement with this result, another study examined the absolute reliability of gait parameters in healthy subjects and found the highest measurement errors in the transverse plane (32). The use of marker clusters in our study appears to improve the reliability of non-sagittal plane kinematic data as opposed to mentioned studies, which could be partly due to reduced skin movement artifact (33).

Regardless of the plane effect, the reliability of LyE of the knee and hip joint was lower than the ankle joint, particularly with the cognitive tasks. This result may be related to the joint angle changes and flexibility of the two joint muscles crossing the hip and knee joints, causing the instantaneous position of the hip and knee joint centers to be more variable than the ankle joint center (34). Also, previous research shows that proximal joints increase variability to prevent damage to distal joints (35). The sensory-perceptual impairments associated with patients with FAI may underlie this protective movement strategy to redistribute the impact from the unstable distal joint (*e.g.*, ankle) to more stable proximal joints (*e.g.*, knee and hip) due to mechanical advantages of the proximal joints (*e.g.*, longer muscle fibers, greater muscle volume, and strength) during dynamic tasks (36).

According to our outcome, which is consistent with the finding of a systematic review (28), the reliability of sagittal and frontal planes was typically higher than 0.80 and 0.70 in most studies, respectively. Nazary-Moghadam *et al*. studied the reliability of knee flexion-extension LyE in people with and without anterior cruciate ligament deficiency under single and dual-task walking (37). Similar to the present study, the knee flexion-extension LyE had high intrasession reliability, with ICC values above 0.70.

The relative intrasession reliability of the auditory Stroop task showed that average reaction times were higher than error ratios in both groups. Some studies used auditory Stroop concurrently with postural tasks. Similarly, all these studies concluded that average reaction time is a more appropriate measure than error ratio (38-40).

The LyE is considered a useful measure in estimating the ability to withstand perturbations in human walking. Several studies (10, 37, 41, 42) have demonstrated lower LyE values of the lower limb joint angles during challenging situations and postural task difficulty in the clinical population compared with those of healthy individuals. Because all these studies were conducted in one session, their findings may be comparable with those of the present study. Moderate to very high intrasession relative reliability in both the FAI and healthy groups indicates that measurement error might be less than the variability between participants; consequently, the possibility of error type II would be limited. An essential point in this study is that the LyE of gait kinematics seems to be a sufficiently reliable measurement when comparisons between the FAI and healthy patient groups are obtained in one session.

The current study had some limitations. First, the findings could be generalized only to males with FAI. Future studies remain to assess the reliability of the LyE of gait kinematics in females with FAI and other groups with a varying history of injury during different motor/cognitive tasks. The other limitation was the small sample size. It suggests performing future research with a larger sample size to have a more precise estimation of the reliability of kinematic measures in subjects with and without FAI. Also, gait testing took place within one session in the present study. Future investigations should also consider evaluating the intersession reliability between sessions to reach a more comprehensive result.

CONCLUSIONS

In normal and dual-task walking, outcomes were comparable and indicated moderate to very high reliability, making it potentially helpful in detecting gait pathology. The low reliability in the hip and knee transverse plane requires consideration in data interpretation.

CONTRIBUTIONS

SSN: conceptualization. TB, SSN: methodology. MY, Z.E: investigation. TB: data analysis. TB, AD, SSN: writing – original draft. TB, AD, SSN: writing – review and editing.

DATA AVAILABILITY

Data are available under reasonable request to the corresponding author.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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