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Intra- and inter-session reliability of countermovement jump and gait analysis in collegiate athletes measured using an inertial measurement unit (BTS G-Walk)

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Abstract

This study assessed the intra- and inter-session reliability of the inertial measurement unit (IMU) in measuring countermovement jump (CMJ) and 10m-walking gait-related outcomes. Thirty collegiate-level athletes (15 males [age: 21.0 ± 2.5 years] and 15 females [age: 21.5 ± 2.1 years]) were recruited to perform CMJs and 10m-walking test that were simultaneously recorded using the commercially available body-worn IMU – BTS G-walk. The coefficient of variation (CV), the analysis of variance with repeated measures (ANOVA), and the interclass correlation coefficient (ICC) were used for intra-session reliability. While the Pearson's correlation coefficient (r) and the ICC were used to analyze inter-session reliability. Measurement of CMJ and 10m-walking test gait variables using the IMU resulted in moderate to excellent intra-session reliability for CMJ (ICC = 0.881 to 0.988) and gait analysis (ICC = 0.807 to 0.978) with acceptable CV (≤10%). Inter-session reliability for CMJ variables ranged from poor to excellent (ICC = 0.134 to 0.963), and 10-m walking test gait analysis variables were moderate to excellent (ICC = 0.683 to 0.931). The IMU (BTS G-walk) provides reliable data for most CMJ and gait variables. Future studies may determine the accuracy of the equipment to monitor changes over time (e.g., after a training intervention).

Keywords: *Plyometric exercise, athletic performance, exercise, sports medicine, athletic performance, human movement*

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RELIABILITY OF JUMP AND GAIT ANALYSIS
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Introduction

Tests, measurements, and evaluations play an important role in sports science settings in monitoring athletes' health and performance (Lacy & Williams, 2018). In this context, an assessment that can fulfill multiple objectives is desirable (e.g., performance benchmarking, fatigue monitoring). The countermovement jump (CMJ) can be used to assess neuromuscular fatigue during different types of training sessions (e.g., endurance running) (García-Pinillos et al., 2021; Gathercole et al., 2015). Indeed, the reliability of CMJ in assessing neuromuscular fatigue has also been reported in a meta-analysis (Claudino et al., 2017). In addition, the CMJ can be used for performance profiling (e.g., force-velocity curve) and to assess post-injury progress and preparedness to return to sports (Bishop et al., 2023). The CMJ can also be used to assess an individual's capability to produce lower body force through a stretch-shortening cycle movement (Van Hooren & Zolotarjova, 2017), an important reflection of an individual's ability to store and use elastic energy (Van Hooren & Zolotarjova, 2017).

Furthermore, besides CMJ performance, gait-related measures may also help in the assessment of human performance preparedness by identifying the likelihood of future running-related lower limb injury among university-level athletes (Gogoi et al., 2021). Moreover, incorporating gait analysis within a training programme may also help identify gait-related injuries (Tao et al., 2012). In addition, gait analysis may be an important assessment tool for athletes undergoing rehabilitation following lower limb injuries (e.g., anterior cruciate ligament reconstruction) (DeVita et al., 1998; Timoney et al., 1993). The CMJ and gait analyses can be performed using different reliable technologies and equipment, such as force platforms (Moir et al., 2009), wireless microelectromechanical-based systems (Requena et al., 2012), linear position transducers (Wadhi et al., 2018), among others. The gold standard for CMJ (force platforms) and gait analyses (3D motion analysis) are usually performed in a laboratory setting with complex and expensive equipment, requiring qualified personnel to operate, laborious measurement protocols, and logistically restricted equipment, likely unavailable to most practitioners (Simon, 2004). However, fast technological advancement in the field allows new and more accessible instruments to be available at an increased rate, such as contact mat (Pueo et al., 2017), photoelectric cells (Glatthorn et al., 2011), and mobile applications (i.e., My Jump App) (Gallardo-Fuentes et al., 2016). Among accessible instruments, an inertial measurement unit (IMU) can be a particularly useful tool to provide an alternative solution to highly sophisticated and costly equipment (Clemente et al., 2022).

The IMU integrates three types of sensors, i.e., accelerometers (inertial acceleration measurement), gyroscopes (angular rotation measurement), and magnetometers (orientation measurement) (O'Reilly et al., 2018) used to measure velocity, orientation, and gravitational force (Camomilla et al., 2018). The IMU is easily portable and can measure different variables such as jump height during vertical jumps (e.g., countermovement jump [CMJ]) (Clemente et al., 2022), barbell velocity during strength training exercises (Clemente et al., 2021), monitor sleep quality (Nam et al., 2016), detect changes of direction (Alanen et al., 2021), and gait analysis (Andrenacci et al., 2021). Some IMUs (e.g., BTS G-walk, Italy) can be used for multiple assessments, including CMJ and gait analyses (Andrenacci et al., 2021).

Although the BTS G-Walk has been found valid and reliable for gait analysis in healthy subjects (mean age: 37.8 years) (De Ridder et al., 2019; Vítečková et al., 2020) and Parkinson's disease patients (Vítečková et al., 2020), its reliability for CMJ and gait analyses in collegiate athlete is under-researched. Indeed, good test reliability is obligatory for athletes, as any error may decrease the precision of the test and increase the smallest detectable change (Hopkins, 2000). Further, in the aforementioned studies, only intra-day reliability was calculated from five trials (De Ridder et al., 2019) or two trials (Vítečková et al., 2020) using an intraclass correlation coefficient (ICC). Therefore, this study aimed to identify the intra- and inter-session reliability of the BTS G-walk sensor for CMJ and gait analysis among male and female collegiate athletes. Based on the available literature on IMU, we hypothesized that the BTS G-walk sensor would demonstrate acceptable reliability for both CMJ and gait analyses.

Methods

Participants

A total of 30 collegiate athletes (i.e., basketball and handball) (15 male athletes [age: 21.0 ± 2.5 years; height: 169.6 ± 4.5 cm; body mass: 68.0 ± 3.9 kg] and 15 female athletes [age: 21.5 ± 2.1 years; height: 163.7 ± 6.6 cm; body mass: 56.7 ± 6.0 kg]) were recruited for the study, all training ≥5 hours per week. The number of participants were chosen based on a similar study conducted to assess the concurrent validity and reliability of BTS G-walk sensor (De Ridder et al., 2019). To be included in the study, the subjects had to be i) free from lower extremity injury in past six months, ii) free from any other injury in the past one month, iii) free from any other musculoskeletal or neuromuscular disorder that could potentially affect their jump and gait. The participants were informed about the study procedures, and informed consent forms were signed. The internal review board of the School of Physical Education and Sports, Rashtriya Raksha University approved this study.

Procedure

A familiarization session was conducted before the start of the data collection, and demographics data (i.e., age, height, body mass) were collected the same day. Thereafter, the experiment took place over a period of three weeks, with two sessions conducted for inter-session analysis and three trials conducted each session for intra-session analysis. The CMJ and gait analyses were conducted on separate days. The data collection took place inside a laboratory with a regulated temperature of 24 °C and was conducted during the same period (i.e., 1400 to 1700 hours).

Countermovement jump

A warm-up of 10 minutes was conducted prior to the CMJ test on each testing day, which included running on the treadmill at a self-selected pace (participants were asked to avoid fatigue) and dynamic stretching of lower limbs (same dynamic stretching protocol was used in all testing days). In addition, the participants were also allowed to practice CMJ prior to the data collection using IMU. Thereafter, to collect data, the IMU (BTS G-walk) was placed on the lower back of each participant using a belt with the center of the device at the fifth lumbar vertebrae (i.e., L5). The subjects were asked to perform a CMJ on a wooden platform with the aim of achieving maximum vertical height following a self-selected knee flexion during countermovement based on a protocol used in previous studies (Kumar et al., 2023; Thapa & Kumar, 2023). However, the flexing of knees was not allowed during the flight. Three trials were conducted for each subject with a recovery period of ~1 minute. All successful trials were used for analysis.

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Gait analysis

The gait analysis was conducted on a concrete floor inside a laboratory. The sensor was placed at the same place (i.e., L5) as mentioned above for CMJ. To record gait data, the 10 m walk test was conducted as mentioned in a previous study (Andrenacci et al., 2021). The participant walked 10 m in a straight line (participants were instructed to walk in their normal pace), thereafter changed direction around a placed cone and returned back to the start point. The participants were asked to stand in an immobile upright position (i.e., orthostatic) before starting. Three trials were conducted for each participant with a recovery period of ~30 seconds. All trials were kept for analysis.

Statistical analysis

The normality of the data was verified using the Shapiro-Wilk test. Intra-session reliability for both the CMJ and gait assessments in the two test sessions (TS1 and TS2) was determined utilizing the calculation of the coefficient of variation (CV), the analysis of variance with repeated measures (ANOVA) and the ICC (using two-way random effects model). The inter-session reliability between both sessions (variation between TS1 and TS2) was calculated using Pearson's correlation coefficient (r) and the ICC (using a two-way random effects model). Differences between TS1 and TS2 mean values were calculated using Student's t-test for related samples. The significance level chosen for the statistical analysis was $p \leq 0.05$. The ICC were interpreted as poor (<0.50), moderate (≥0.50 – <0.75), good (≥0.75 – <0.90), and excellent (>0.90) reliability based on the lower bound of the 95% confidence interval (CI) (Koo & Li, 2016). The Pearson's correlation coefficient was interpreted as low (r = 0.1 – 0.3), moderate (r= ≥0.3 – 0.5) and high (r = ≥0.50) (Cohen, 1992). The CV represented the typical error of measurements expressed as a percentage of the mean, and a value ≤10% was considered acceptable (Cormack et al., 2008). All data were analysed using SPSS for Windows (version 28; SPSS Inc, Armonk, NY).

Results

The mean and standard deviation obtained during the CMJ and gait assessments are reported in Table 1 and Table 2, respectively.

Table 1. Mean and standard deviation (SD) of countermovement jump variables during the testing sessions.

	Testing Session 1						Testing Session 2					
	Combined		Male		Female		Combined		Male		Female	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Jump height (cm)	27.14	5.90	31.10	5.84	23.17	2.10	26.54	5.61	30.84	4.87	22.23	1.37
	27.22	5.91	31.26	5.71	23.17	2.16	26.61	5.97	31.13	5.11	22.08	1.93
	27.36	6.12	31.85	5.57	22.87	1.86	26.71	6.23	31.51	5.44	21.91	1.27
Take-off force (kN)	0.76	0.28	0.85	0.25	0.66	0.28	0.72	0.28	0.92	0.23	0.53	0.17
	0.77	0.29	0.86	0.26	0.67	0.30	0.71	0.25	0.88	0.21	0.54	0.16
	0.78	0.27	0.89	0.25	0.68	0.26	0.71	0.27	0.91	0.20	0.51	0.16
Impact force (kN)	0.71	0.26	0.84	0.23	0.58	0.21	0.77	0.28	0.92	0.21	0.62	0.25
	0.72	0.28	0.86	0.26	0.58	0.23	0.76	0.27	0.91	0.20	0.62	0.26
	0.72	0.25	0.84	0.22	0.60	0.23	0.73	0.28	0.92	0.21	0.54	0.19
Maximal concentric power (kW)	2.87	0.79	3.31	0.74	2.44	0.60	2.81	0.94	3.44	0.81	2.18	0.56
	2.87	0.79	3.29	0.71	2.45	0.64	2.79	0.88	3.37	0.72	2.21	0.63
	2.92	0.85	3.43	0.73	2.42	0.64	2.80	0.91	3.45	0.74	2.14	0.50
Average concentric phase speed (m/s)	1.28	0.21	1.28	0.24	1.28	0.19	1.30	0.17	1.28	0.21	1.32	0.12
	1.32	0.22	1.36	0.25	1.29	0.19	1.33	0.15	1.32	0.19	1.33	0.10
	1.32	0.24	1.34	0.28	1.31	0.19	1.34	0.19	1.33	0.25	1.36	0.12
Peak concentric speed (m/s)	2.55	0.26	2.68	0.28	2.41	0.15	2.52	0.28	2.71	0.25	2.34	0.15
	2.56	0.27	2.68	0.28	2.44	0.20	2.52	0.27	2.70	0.25	2.35	0.17
	2.56	0.27	2.71	0.27	2.41	0.19	2.53	0.29	2.71	0.27	2.34	0.17
Take-off speed (m/s)	2.40	0.27	2.45	0.33	2.34	0.20	2.36	0.28	2.48	0.33	2.24	0.14
	2.40	0.29	2.46	0.34	2.33	0.21	2.36	0.28	2.48	0.32	2.24	0.18
	2.36	0.30	2.42	0.37	2.29	0.20	2.37	0.29	2.50	0.33	2.25	0.17

Table 2. Mean and standard deviation (SD) of gait variables during the testing sessions.

	Testing Session 1						Testing Session 2					
	Combined		Male		Female		Combined		Male		Female	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Speed (m/s)	1.17	0.17	1.14	0.20	1.20	0.14	1.22	0.20	1.18	0.21	1.27	0.18
	1.19	0.16	1.14	0.17	1.24	0.14	1.23	0.19	1.17	0.18	1.29	0.19
	1.23	0.18	1.18	0.19	1.27	0.16	1.25	0.21	1.19	0.22	1.31	0.20

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Table 2. Mean and standard deviation (SD) of gait variables during the testing sessions.

	Testing Session 1						Testing Session 2					
	Combined		Male		Female		Combined		Male		Female	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	110.35	6.81	106.25	6.37	114.44	4.40	112.94	7.97	108.07	5.27	117.80	7.30
Cadence (steps/min)	111.67	6.89	107.27	5.49	116.07	5.16	112.79	7.71	108.05	5.11	117.52	7.00
	113.33	7.40	108.82	5.59	117.83	6.23	113.51	8.14	108.57	5.34	118.45	7.50
	60.48	2.04	60.73	1.67	60.24	2.39	60.44	2.12	60.05	1.79	60.83	2.42
Stance phase left leg (%cycle)	60.33	2.07	60.65	1.57	60.01	2.49	60.21	2.02	59.60	1.56	60.81	2.28
	60.21	2.29	60.41	2.15	60.02	2.48	60.30	1.88	59.79	1.58	60.82	2.06
	60.01	2.42	60.95	2.80	59.08	1.55	60.21	2.42	60.59	2.46	59.82	2.39
Stance phase right leg (%cycle)	59.79	1.96	60.41	1.84	59.17	1.94	60.07	2.34	60.72	2.30	59.43	2.27
	59.55	1.84	59.78	2.11	59.33	1.57	59.56	2.27	60.07	2.07	59.05	2.41
	39.70	2.11	39.66	1.84	39.74	2.42	39.72	2.15	40.27	1.76	39.17	2.42
Swing phase left leg (%cycle)	39.88	2.14	39.78	1.80	39.99	2.49	39.90	2.08	40.60	1.63	39.19	2.28
	39.84	2.32	39.77	2.17	39.91	2.53	39.81	1.86	40.44	1.44	39.18	2.06
	40.44	1.80	39.98	1.98	40.90	1.53	39.79	2.42	39.41	2.46	40.18	2.39
Swing phase right leg (%cycle)	40.32	2.08	39.81	2.16	40.83	1.94	40.01	2.44	39.43	2.55	40.58	2.26
	40.36	2.10	40.05	2.54	40.67	1.57	40.31	2.55	39.62	2.62	41.00	2.37
	9.66	1.63	10.13	1.33	9.19	1.80	10.17	2.19	10.20	1.76	10.13	2.61
First double support phase left leg (%cycle)	9.75	1.71	10.23	1.40	9.27	1.90	10.09	2.10	10.26	1.70	9.91	2.48
	9.52	1.87	9.97	1.93	9.06	1.76	9.87	1.88	10.07	1.66	9.66	2.12
	10.53	1.81	10.85	1.54	10.21	2.05	10.38	1.81	10.40	1.84	10.36	1.85
First double support phase right leg (%cycle)	10.49	1.75	10.75	1.42	10.23	2.04	10.43	1.84	10.44	1.94	10.41	1.82
	10.49	2.08	10.58	1.99	10.40	2.23	10.34	1.83	10.38	1.80	10.29	1.93
	40.33	1.63	39.71	1.54	40.95	1.53	39.94	2.30	39.44	2.22	40.43	2.35
Single support phase left leg (%cycle)	39.85	2.83	38.98	3.32	40.73	1.99	39.99	2.45	39.28	2.43	40.70	2.34
	40.27	1.90	39.78	2.21	40.75	1.45	40.24	2.25	39.49	1.93	40.99	2.36
	39.50	2.07	39.28	1.82	39.71	2.35	39.69	2.08	40.03	1.65	39.35	2.44
Single support phase right leg (%cycle)	39.73	1.94	39.65	1.54	39.81	2.32	39.74	2.01	40.38	1.55	39.11	2.27
	39.82	2.21	39.74	2.13	39.89	2.37	39.63	1.80	40.16	1.47	39.11	1.99
	1.26	0.16	1.27	0.18	1.25	0.13	1.29	0.16	1.29	0.17	1.29	0.15
Stride length left leg (m)	1.28	0.15	1.28	0.18	1.28	0.13	1.30	0.16	1.29	0.17	1.31	0.15
	1.29	0.16	1.29	0.18	1.29	0.13	1.32	0.17	1.31	0.18	1.33	0.15
	1.25	0.13	1.24	0.14	1.25	0.14	1.28	0.14	1.25	0.12	1.30	0.15
Stride length right leg (m)	1.26	0.13	1.25	0.14	1.28	0.13	1.30	0.15	1.28	0.14	1.31	0.15
	1.28	0.14	1.26	0.14	1.29	0.14	1.30	0.15	1.27	0.14	1.33	0.16
	50.04	1.62	50.44	1.86	49.63	1.28	49.97	1.59	50.11	1.90	49.82	1.25
Step length left leg (%stride length)	49.75	1.42	50.19	1.34	49.32	1.42	49.94	1.63	50.18	2.03	49.70	1.12
	49.85	1.79	50.52	1.78	49.18	1.60	50.02	1.47	50.32	1.76	49.73	1.10
	50.21	1.55	50.05	1.81	50.37	1.28	50.02	1.59	49.85	1.91	50.18	1.25
Step length right leg (%stride length)	49.98	2.96	49.28	3.89	50.68	1.42	50.14	1.52	49.95	1.86	50.34	1.13
	50.23	1.88	49.66	2.01	50.81	1.59	49.89	1.60	49.51	1.95	50.28	1.09

Intra- and inter-session reliability for CMJ

The detailed results of intra-session analyses for CMJ are presented in Table 3. The intra-session ICC values were good to excellent for the CMJ variables in both test sessions (TS1 ICC = 0.881 to 0.988; TS2 ICC = 0.885 to 0.993). In addition, similar reliability results were obtained for males and females. The CV was acceptable (≤10%) for all variables. The repeated measures ANOVA revealed no difference between the three trials during TS1 or TS2 except for CMJ average speed concentric phase ($p = 0.046$) during TS2.

The detailed results for inter-session reliability analyses are presented in Table 4. The inter-session ICC values ranged between poor to excellent for the CMJ variables between TS1 and TS2 (ICC = 0.134 to 0.963). There were moderate to high

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Table 3. Intra-session reliability** for countermovement during testing session 1 and 2.

	TS1			TS2		
	ANOVA p-value	ICC	CV (%)	ANOVA p-value	ICC	CV (%)
Jump height (cm)						
All	0.805	0.988	3.90	0.807	0.989	4.03
Females	0.405	0.958	2.20	0.553	0.786	1.51
Males	0.321	0.978	4.59	0.327	0.984	4.20
Take-off force (kN)						
All	0.470	0.988	6.50	0.549	0.952	9.52
Females	0.848	0.979	10.43	0.468	0.954	7.63
Males	0.292	0.975	7.39	0.221	0.973	6.00
Impact force (kN)						
All	0.863	0.962	6.40	0.347	0.949	6.35
Females	0.515	0.977	9.55	0.106	0.937	9.76
Males	0.626	0.922	6.63	0.805	0.894	5.20
Maximum concentric power (kW)						
All	0.368	0.986	5.05	0.839	0.993	5.90
Females	0.817	0.989	6.57	0.334	0.990	6.62
Males	0.036	0.973	5.48	0.207	0.984	5.61
Average speed concentric phase (m/s)						
All	0.256	0.913	2.90	0.046*	0.885	2.19
Females	0.557	0.966	3.71	0.209	0.863	1.94
Males	0.296	0.882	4.53	0.126	0.894	3.99
Peak concentric speed (m/s)						
All	0.780	0.966	1.80	0.956	0.983	1.98
Females	0.515	0.905	1.78	0.803	0.971	1.71
Males	0.457	0.974	2.60	0.727	0.975	2.40
Take-off speed (m/s)						
All	0.693	0.881	1.97	0.532	0.984	2.16
Females	0.588	0.894	2.07	0.837	0.961	1.82
Males	0.827	0.871	3.27	0.609	0.984	3.33

*: denotes statistical significance; **: from 3 countermovement jumps trials; CV: coefficient of variation; ICC: intraclass correlation coefficient.

significant correlations between TS1 and TS2 for jump height, take-off force, impact force, max concentric power, average speed concentric phase, peak concentric speed, and take-off speed (r = 0.411 to 0.931). The Student's t-test revealed significant differences between TS1 and TS2 for impact force, average speed concentric phase, peak concentric speed and

Table 4. Reliability for countermovement jump between testing session 1 and 2.

	Student's t p-value	Intraclass correlation coefficient	Pearson's r
Jump height (cm)			
All	0.165	0.963	0.931**
Females	0.129	0.415	0.298
Males	0.580	0.938	0.882**
Take-off force (kN)			
All	0.061	0.859	0.770**
Females	0.006a	0.666	0.767**
Males	0.380	0.920	0.868**
Impact force (kN)			
All	<0.001[a]	0.287	0.545**
Females	0.001[a]	0.204	0.706**
Males	<0.001[a]	0.101	0.199

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Table 4. Reliability for countermovement jump between testing session 1 and 2.

	Student's t p-value	Intraclass correlation coefficient	Pearson's r
Maximum concentric power (kW)			
All	0.082	0.605	0.623**
Females	0.350	0.703	0.550**
Males	0.032	0.342	0.400
Average speed concentric phase (m/s)			
All	<0.001[a]	0.194	0.411*
Females	0.176	0.332	0.249
Males	<0.001[a]	0.171	0.531
Peak concentric speed (m/s)			
All	0.002[a]	0.134	0.471**
Females	0.088	0.815	0.719**
Males	<0.001[a]	0.017	0.103
Take-off speed (m/s)			
All	0.002[a]	0.184	0.595**
Females	0.083	0.684	0.570**
Males	<0.001[a]	0.160	0.735**

[a] – significant difference between testing session 1 and 2; *Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

take off speed (p = <0.001 to 0.002). Furthermore, significant differences were observed among females for take-off force and impact force, and among males for impact force, average speed concentric phase, peak concentric speed, and take-off speed (p = <0.001 to 0.006).

Intra- and inter-session reliability for gait analysis

The detailed results of intra-session gait analyses are presented in Table 5. The intra-session ICC values were moderate to excellent in both test sessions (TS1 ICC = 0.807 to 0.978; TS2 ICC = 0.881 to 0.969) for the gait analysis variables. However, the

Table 5. Intra-session reliability for gait analysis during testing sessions 1 and 2.

	TS1			TS2		
	ANOVA p-value	ICC	CV (%)	ANOVA p-value	ICC	CV (%)
Speed (m/s)						
All	0.008*	0.939	2.52	0.090	0.969	1.48
Females	0.069	0.907	2.91	0.249	0.924	3.64
Males	0.090	0.956	4.00	0.421	0.981	0.95
Cadence (steps/min)						
All	0.001*	0.941	1.10	0.234	0.955	1.23
Females	0.025*	0.832	1.05	0.411	0.957	1.48
Males	0.024*	0.950	1.35	0.624	0.976	0.94
Stance phase left leg (%cycle)						
All	0.474	0.945	0.60	0.476	0.956	0.58
Females	0.449	0.962	1.02	0.999	0.955	0.91
Males	0.706	0.916	0.72	0.285	0.954	0.68
Stance phase right leg (%cycle)						
All	0.510	0.807	0.54	0.004*	0.960	0.69
Females	0.748	0.930	0.61	0.024	0.968	0.99
Males	0.201	0.685	0.77	0.122	0.949	0.69
Swing phase left leg (%cycle)						
All	0.420	0.953	0.95	0.595	0.962	0.90
Females	0.380	0.965	1.55	0.999	0.955	1.42
Males	0.876	0.937	1.18	0.140	0.965	0.99

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Table 5. Intra-session reliability for gait analysis during testing sessions 1 and 2.

	TS1			TS2		
	ANOVA p-value	ICC	CV (%)	ANOVA p-value	ICC	CV (%)
Swing phase right leg (%cycle)						
All	0.826	0.933	0.85	0.097	0.959	1.80
Females	0.764	0.930	1.00	0.008*	0.969	1.46
Males	0.762	0.933	1.36	0.862	0.948	0.99
First double support phase left leg (%cycle)						
All	0.523	0.931	3.10	0.380	0.950	3.57
Females	0.379	0.954	4.89	0.451	0.970	6.12
Males	0.734	0.855	3.61	0.872	0.907	1.57
First double support phase right leg (%cycle)						
All	0.974	0.922	3.00	0.872	0.947	3.05
Females	0.797	0.957	5.08	0.896	0.971	4.81
Males	0.838	0.859	3.53	0.975	0.968	3.97
Single support phase left leg (%cycle)						
All	0.472	0.843	0.87	0.222	0.967	1.03
Females	0.646	0.931	0.99	0.131	0.944	1.54
Males	0.558	0.766	1.33	0.776	0.959	4.47
Single support phase right leg (%cycle)						
All	0.292	0.942	1.00	0.845	0.941	0.85
Females	0.840	0.968	1.47	0.779	0.923	1.40
Males	0.338	0.699	1.02	0.193	0.926	1.35
Stride length left leg (m)						
All	0.040*	0.978	2.20	0.252	0.963	1.90
Females	0.109	0.848	2.59	0.122	0.969	2.90
Males	0.383	0.985	3.67	0.098	0.995	3.47
Stride length right leg (m)						
All	0.026*	0.968	1.90	0.018*	0.961	0.55
Females	0.086	0.906	2.58	0.077	0.970	2.97
Males	0.328	0.977	2.80	0.040*	0.962	2.60
Step length left leg (%stride length)						
All	0.085	0.954	0.57	0.822	0.915	0.55
Females	0.024*	0.958	0.70	0.818	0.914	0.55
Males	0.267	0.963	0.83	0.487	0.980	0.96
Step length right leg (%stride length)						
All	0.790	0.880	0.72	0.223	0.881	3.15
Females	0.025*	0.932	0.69	0.667	0.921	0.55
Males	0.196	0.960	1.25	0.107	0.974	0.97

*: denotes statistical significance; ICC: intraclass correlation coefficient; CV: coefficient of variation.

ICC values were good for cadence and stride length in females during TS1. In addition, ICC values were moderate for the stance phase (left leg) and single support phase (right leg) and good for the first double support phase (both left and right legs), single support phase (left leg), and stride length (left leg) among males during TS1. Other variables achieved excellent ICC values (>0.90) during TS1 and TS2 in males and females. The CV was acceptable (≤10%) for all variables in both TS. The repeated measure ANOVA revealed a significant difference for all participants in speed, cadence, and stride length (both legs) during TS1, and in the stance phase (right leg) and stride length (right leg) during TS2.

The detailed results for inter-session reliability gait analysis variables are presented in Table 6. The between TS1 and TS2 inter-session ICC values ranged between moderate to excellent (ICC = 0.683 to 0.931). However, ICC values among females were poor for step length (left leg) (ICC = 0.485). Further, a high significant Pearson correlation coefficient was obtained for each variable between TS1 and TS2 (r = 0.528 to 0.880). In addition, the Student's t-test reported a significant difference in gait speed between TS1 and TS2 ($p = 0.045$). Furthermore, significant differences were reported in females' speed ($p = 0.030$) and stride length (left leg) ($p = 0.017$), and in stance phase (left leg) for males ($p = 0.037$).

Table 6. Inter-session reliability for measure of gait between testing session 1 and 2.

	Student's t p-value	Intraclass correlation coefficient	Pearson's r
Speed (m/s)			
All	0.045a	0.878	0.813**
Females	0.030a	0.866	0.870**
Males	0.803	0.859	0.753**
Cadence (steps/min)			
All	0.127	0.887	0.811**
Females	0.168	0.781	0.700**
Males	0.382	0.814	0.682**
Stance phase left leg (%cycle)			
All	0.924	0.821	0.690**
Females	0.072	0.867	0/798**
Males	0.037a	0.764	0.677**
Stance phase right leg (%cycle)			
All	0.644	0.683	0.528**
Females	0.667	0.609	0.455
Males	0.875	0.698	0.529*
Swing phase left leg (%cycle)			
All	0.996	0.836	0.712**
Females	0.082	0.872	0.803**
Males	0.061	0.788	0.700**
Swing phase right leg (%cycle)			
All	0.303	0.796	0.681**
Females	0.697	0.611	0.456
Males	0.224	0.891	.818**
First double support phase left leg (%cycle)			
All	0.199	0.725	0.584**
Females	0.154	0.727	0.618*
Males	0.849	0.719	0.548*
First double support phase right leg (%cycle)			
All	0.666	0.774	0.626**
Females	0.862	0.768	0.614*
Males	0.382	0.796	.671**
Single support phase left leg (%cycle)			
All	0.763	0.796	0.664**
Females	0.851	0.610	0.453
Males	0.803	0.677	.788**
Single support phase right leg (%cycle)			
All	0.972	0.821	0.690**
Females	0.120	0.869	0.789**
Males	0.940	0.745	0.633*
Stride length left leg (m)			
All	0.061	0.931	0.880**
Females	0.017a	0.943	0.931**
Males	0.156	0.927	0.860**
Stride length right leg (m)			
All	0.645	0.910	0.850**
Females	0.329	0.950	0.944*
Males	0.271	0.861	0.754**

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Table 6. Inter-session reliability for measure of gait between testing session 1 and 2.

	Student's t p-value	Intraclass correlation coefficient	Pearson's r
Step length left leg (%stride length)			
All	0.658	0.793	0.651**
Females	0.280	0.485	0.331
Males	0.508	0.878	0.783**
Step length right leg (%stride length)			
All	0.645	0.805	0.693**
Females	0.329	0.563	0.403
Males	0.792	0.862	0.722**

[a] – significant difference between testing session 1 and 2; *Correlation is significant at the 0.05 level (2-tailed);
**Correlation is significant at the 0.01 level (2-tailed).

Discussion

The aim of the study was twofold: firstly, to investigate the reliability of an IMU (BTS G-walk) to measure countermovement jump, and secondly, to investigate the reliability of the same instruments to measure the gait parameters among male and female collegiate athletes. For the study's first aim, the findings demonstrated the IMU to have good to excellent intra-session ICC values in both sessions for CMJ variables, indicating high reliability. Moreover, when the participants were categorized based on sex, similar results were obtained for both males and females, which indicates that the instrument is equally reliable for both sexes. In addition, acceptable CV values (i.e., typical error of measurement) were reported for all CMJ variables. Indeed, a previous systematic review has reported different IMUs (e.g., Myotest Pro, Vert Classic) to be valid and reliable for measuring jump height (Clemente et al., 2022). However, the inter-session ICC values ranged from poor (i.e., impact force, average speed concentric phase, peak concentric speed, take-off speed) to excellent (i.e., jump height), indicating that the reliability of the CMJ variables varied between TS1 and TS2. In addition, differences were also noted in the results for inter-session analyses (i.e., TS1 versus TS2) between sexes (Table 2). For example, jump height was significantly correlated between TS1 and TS2 for males but not for females. In contrast, impact force was significantly correlated between TS1 and TS2 for females but not for males. These differences in the results for both sexes may be plausible due to the differences in training sessions the participants were involved in during the course of data collection. Both male and female athletes were involved in separate training programs in their respective sports preparing for the inter-university competitions, due to which the training load could not be controlled, which may have resulted in such findings. Nevertheless, moderate to high significant correlations were observed for most of the CMJ variables between the two TS, indicating that the instrument may be generally reliable over time. Moreover, the differences obtained between the scores in the CMJ variables between TS1 and TS2, with good intra-session ICC within each TS, shows the ability of the IMU to detect the changes that may be possible due to unpredictable reasons (e.g., fatigue among the participants due to factors that couldn't be controlled in this study). Indeed, the CMJ test is valid to assess the neuromuscular fatigue of an athlete (Bishop et al., 2023; Claudino et al., 2017). However, if fatigue is related to the poor reliability values noted between TS1 and TS2 (Table 4), it is not clear, and only speculation would be possible.

For the study's second aim, the findings demonstrated moderate to excellent reliability for most gait analysis variables in both intra-session and inter-session testing. This suggests that the IMU can be a reliable tool for measuring gait patterns and monitoring changes over time among collegiate athletes. These findings are consistent with previous studies using IMUs from different manufacturers (e.g., Xsens, Opal) (Kobsar et al., 2020). The high intra-session reliability of the IMU data in this study can be related to the selected IMU placement (lower back), allowing predictable and consistent sensor position during walking, thus minimizing collected data variability due to sensor displacement (Niswander et al., 2020). However, some sex-specific differences in ICC values were observed, particularly for cadence and stride length in females, and for stance phase, single support phase, first double support phase, and stride length in males. These findings indicate that sex should be considered when analysing gait patterns using the IMU. The typical error expressed as CV was acceptable for all variables in both TS, indicating that the measurements taken by the IMU were accurate and precise. However, the significant differences observed between TS1 and TS2 in speed and stride length (left) for females, and in stance phase (left) for males, suggest some limitations and potential sources of error associated with the use of the IMU instrument. Indeed, caution should be taken when interpreting changes in gait patterns over time, as factors such as changes in speed can affect gait analysis results (Fukuchi et al., 2019). Additionally, while IMUs may be a reliable tool for gait analysis, they should not be used as the sole method for gait analysis. Rather, IMU data may be complemented with other measures of gait, such as video analysis or force plate data if available, to ensure more holistic assessments.

There are some potential limitations of this study that should be acknowledged. Firstly, the training load of the athletes could not be controlled during the two TS. Secondly, the study included only collegiate level basketball and handball athletes. Therefore, the results arising from this study should be used with caution for other sports athletes as well as high-level athletes. Thirdly, although a pilot study (n = 16) reported the IMU sensor to be valid and reliable (concurrent to MyJump 2 [ICC = 0.96, r = 0.973, mean difference = 0.2 ± 1.3, paired t test p = 0.550]) to measure the CMJ height. The concurrent measurement of CMJs with force platform (or other validated IMUs) would also help in validating other kinetic variables along with the jump height.

Conclusion

The IMU BTS G-walk is generally reliable for measuring CMJ variables, with some variation in reliability between males and females and between TS. The significant differences observed between TS and between sex suggest that caution should be exercised when interpreting these results and that further research is necessary to understand the factors that may influence the reliability of the instrument for different variables and populations. In addition, the IMU BTS G-walk can also be a reliable tool for measuring gait patterns and monitoring changes over time, with good to excellent reliability for most gait analysis variables among collegiate athletes. However, sex-specific differences and potential sources of error should be carefully considered when interpreting gait analysis results. Further investigation is also needed to better understand the factors contributing to these differences and to refine gait analysis protocols accordingly.

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Availability of data and material

All data generated or analyzed during this study will be/are included in the published article as Table(s). Any other data requirement can be directed to the corresponding author upon reasonable request.

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