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Reliability and criterion validity of a wearable IMU for ankle joint position sense: agreement with isokinetic dynamometry and discrimination of chronic ankle instability

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Abstract

Background Chronic ankle instability (CAI) impairs joint position sense (JPS) and increase the risk of reinjury. Inertial measurement units (IMUs) are cost-effective and portable, but their reliability and validity for ankle JPS assessment remain uncertain. This study aimed to evaluate the reliability and concurrent validity of IMU-based ankle JPS assessment against an isokinetic dynamometer and to compare JPS errors between individuals with CAI and healthy controls.

Methods In a prospective, assessor-blinded, cross-sectional study, adults with CAI (Cumberland Ankle Instability Tool ≤ 24) and matched controls performed active joint position reproduction tasks in plantarflexion, dorsiflexion, inversion, and eversion with vision occluded. Two IMU sensors recorded joint angles concurrently with a Contrex isokinetic dynamometer (reference standard). Absolute error (AE, °) was the primary outcome. Reliability was quantified using intraclass correlation coefficients (ICC) of intra-session reliability, standard error of measurement, and minimal detectable change; concurrent validity was examined with Bland–Altman analyses. Between-group differences and diagnostic utility were evaluated using group comparisons and receiver operating characteristic (ROC) analyses.

Results Both the isokinetic dynamometer and the IMU demonstrated good-to-excellent intra-session reliability (dynamometer ICC 0.91–0.96; IMU 0.83–0.90), with larger SEM and MDC₉₅ values for the IMU. Bland–Altman analyses showed small negative biases (approximately -0.4° to -2.6°) and 95% limits of agreement generally within about $\pm 5^\circ$ for plantarflexion, dorsiflexion, and inversion, with somewhat wider limits in eversion. Compared with controls, participants with chronic ankle instability exhibited significantly greater absolute JPS errors in plantarflexion, dorsiflexion, and inversion on both devices, and in eversion when assessed by the IMU. ROC analyses showed

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excellent discrimination for plantarflexion (AUC 0.93 for the dynamometer, 0.91 for the IMU), good discrimination for dorsiflexion and inversion, and limited, non-significant discrimination for eversion.

Conclusion IMU-based ankle JPS testing demonstrates good reliability and clinically acceptable agreement with isokinetic dynamometry while detecting proprioceptive deficits in CAI, particularly in plantarflexion, dorsiflexion, and inversion. It appears to be a practical tool for clinical and sports settings, although eversion measurements were more variable and future studies should confirm these findings in larger samples and dynamic, multi-planar tasks.

Keywords Inertial measurement unit, Ankle joint position sense, Proprioception, Chronic ankle instability, Isokinetic dynamometer, Reliability, Validity, Bland–Altman, ROC analysis

Introduction

According to earlier studies, patients with chronic ankle instability (CAI) exhibit markedly reduced joint position sense (JPS) in the inversion and eversion directions of the affected ankle compared with healthy individuals [1]. As JPS primarily encodes information regarding joint position and angle, the central nervous system (CNS) can flexibly modulate joint position control in response to task demands, thereby ensuring stable joint posture [2]. Therefore, reduced JPS is associated with impaired motor function and an increased risk of ankle-related sports injuries [3]. Numerous studies have employed various measurement techniques to identify specific differences in ankle JPS between patients with CAI and healthy controls. However, current research findings regarding which specific motion directions exhibit impaired JPS in CAI patients relative to healthy controls remain inconsistent due to variations in testing protocols and equipment.

Currently, the assessment of JPS is mainly performed using the joint position reproduction (JPR) test [4]. The devices employed include electronic goniometers [5], isokinetic dynamometers [6], and electronic motion monitoring equipment, which further encompasses camera-based motion capture systems, 3D calibration frames, and inertial measurement units (IMUs) [7]. Among these, JPS testing with an isokinetic dynamometer by positioning the limb at a predetermined angle has been widely accepted [8]. However, due to the large size of isokinetic dynamometers, they are not commonly used in clinical evaluations. Although electronic goniometers and camera-based motion capture systems can also provide reliable data, their high cost, cumbersome testing procedures, and complex data analysis pose practical challenges.

In contrast, IMUs are inexpensive, portable, and convenient for testing and are commonly employed to collect data during dynamic activities such as running or jumping [9]. Recent studies have demonstrated good agreement between joint angle measurements obtained using IMUs and those measured with optical motion capture systems [10]. Furthermore, IMUs have been applied in the evaluation of proprioception of the cervical spine and knee joints [11, 12], showing good reliability and validity

in specific directions. Nevertheless, since the cervical spine and knee joint differ fundamentally from the ankle joint in terms of joint type and movement patterns, the reliability and validity of IMU-based JPS assessment for the ankle remain uncertain. Although previous 2 studies have attempted to measure ankle JPS using smartphone or tablet applications (equipped with gyroscopes and accelerometers), the results have been unsatisfactory; for example, ankle JPS required up to ten repeated trials to achieve acceptable test–retest reliability [13]. Moreover, several methodological flaws were noted, such as the absence of Bland–Altman consistency analysis and missing reports of the standard error of measurement (SEM) and minimal detectable change (MDC) [14]. Therefore, the use of smartphones for ankle JPS assessment may still have considerable limitations. In contrast to smartphones, professional IMU sensors provide superior resistance to magnetic interference, smaller device size, and more rigorous sensor-to-segment calibration procedures, which may confer higher sensitivity and reproducibility in ankle angle measurement—advantages that smartphones cannot offer [15]. Hence, it is necessary to explore the reliability and concurrent validity of IMUs for ankle JPS testing. To the best of our knowledge, the present study may be the first to investigate this issue.

In summary, to address the current research gap regarding the reliability and concurrent validity of IMUs for ankle JPS assessment, the present prospective, cross-sectional, controlled study was designed to evaluate the intra-session reliability and measurement accuracy of IMU-based ankle JPS testing in both healthy individuals and patients with CAI, using a Contrex isokinetic dynamometer as the reference standard. In addition, we examined between-group differences in ankle JPS errors and explored the diagnostic utility of ankle JPS measures in different movement directions for discriminating chronic ankle instability from healthy status using ROC analyses. We hypothesized that (1) IMU-based ankle JPS measurements would demonstrate good intra-session reliability (expected ICC > 0.80) and a high level of agreement with isokinetic dynamometer measurements (no clinically relevant systematic bias and acceptable limits of agreement), and that (2) compared with healthy individuals,

participants with chronic ankle instability would exhibit significantly greater absolute errors in ankle JPS testing, with ankle JPS errors—particularly in specific directions—showing meaningful discriminatory performance in ROC analyses. The findings of this study are expected to provide robust evidence supporting IMU-based proprioceptive assessment of the ankle and to lay a foundation for the clinical adoption of portable tools for screening and monitoring proprioceptive deficits.

Methods

Study design

This prospective, assessor-blinded, cross-sectional controlled study was conducted in compliance with the Declaration of Helsinki and received Institutional Review Board approval (No. 2025014).

Participants

Inclusion criteria

- Healthy Control (CON): Individuals with regular exercise habits engage in physical activity at least twice weekly. No history of significant ankle sprain or other major lower-limb injury.
- Chronic Ankle Instability (CAI): Individuals with regular exercise habits engage in physical activity at least twice weekly; (1) At least one severe ankle sprain in the year prior to the examination; (2) Ankle instability, giving away or recurrent sprain sensation, and (3) a score of less than 24 on the Cumberland Ankle Instability Scale [16, 17].

Exclusion criteria

- History of lower-limb fracture or surgery.
- Ankle sprain within the past 6 months.
- Acute musculoskeletal injury of other lower-limb joints within 3 months.
- Visual or vestibular disorders.
- Genetic or metabolic diseases.
- Clinically relevant postural syndromes (e.g., postural deformities or malalignment).

Instrumentation

A wearable IMU system (MyoMotion, Noraxon USA, Scottsdale, AZ, USA) and an isokinetic dynamometer (Contrex MJ, multi-joint assessment system) were used concurrently. To minimize confounding, participants were instructed to avoid vigorous lower-limb exercise for 48 h before testing.

- IMU: Two wireless sensors (triaxial accelerometer and gyroscope) were secured on the test limb with elastic straps: one on the distal tibia (anteromedial aspect) and one on the dorsum of the foot (near the second metatarsal). Following skin preparation, a sensor-to-segment calibration was performed in anatomical neutral (ankle neutral; foot perpendicular to the floor), setting the angle at 0°. Sampling frequency was 100 Hz. Joint angle data were recorded in real time using MyoResearch software.
- Isokinetic Dynamometer: The lower leg was stabilized in the dynamometer fixture, with the foot strapped to the footplate and aligned to the anatomical ankle axis. During active testing, the dynamometer served as the reference angle measurement. The device's angular resolution is 0.1°, and its measurement accuracy has been validated through calibration and is widely accepted as a reference standard.

Procedures

- Preparation: Upon arrival, participants completed a 5-minute constant-load cycle warm-up, followed by dynamic ankle mobility exercises. Participants were then seated in the dynamometer with the test limb secured. Opaque eye masks were worn during all trials to eliminate visual input. The assessor explained the tasks and provided two familiarization trials of active joint position reproduction (aJPR). Additional practice trials were permitted until task comprehension was confirmed (Fig. 1).
- Target-Angle Assignment: To minimize learning and order effects, the sequence of target angles across directions (plantarflexion, dorsiflexion, inversion, eversion) was randomized. For each trial, the ankle was moved to the target angle and held for 5 s to encode the position, then returned to neutral (0°) [18].
- Active Joint Position Sense (aJPS) Task: With vision occluded, participants actively reproduced the memorized target angle and verbally indicated “stop” when they perceived a match. To minimize compensatory movements, they were instructed to move only at the ankle and to avoid hip or knee motion, trunk leaning or rotation, toe gripping, and movements of the contralateral leg. The assessor continuously monitored for these compensations during each trial. The concurrent angles were recorded from the dynamometer and the corresponding IMU angle was extracted. Each

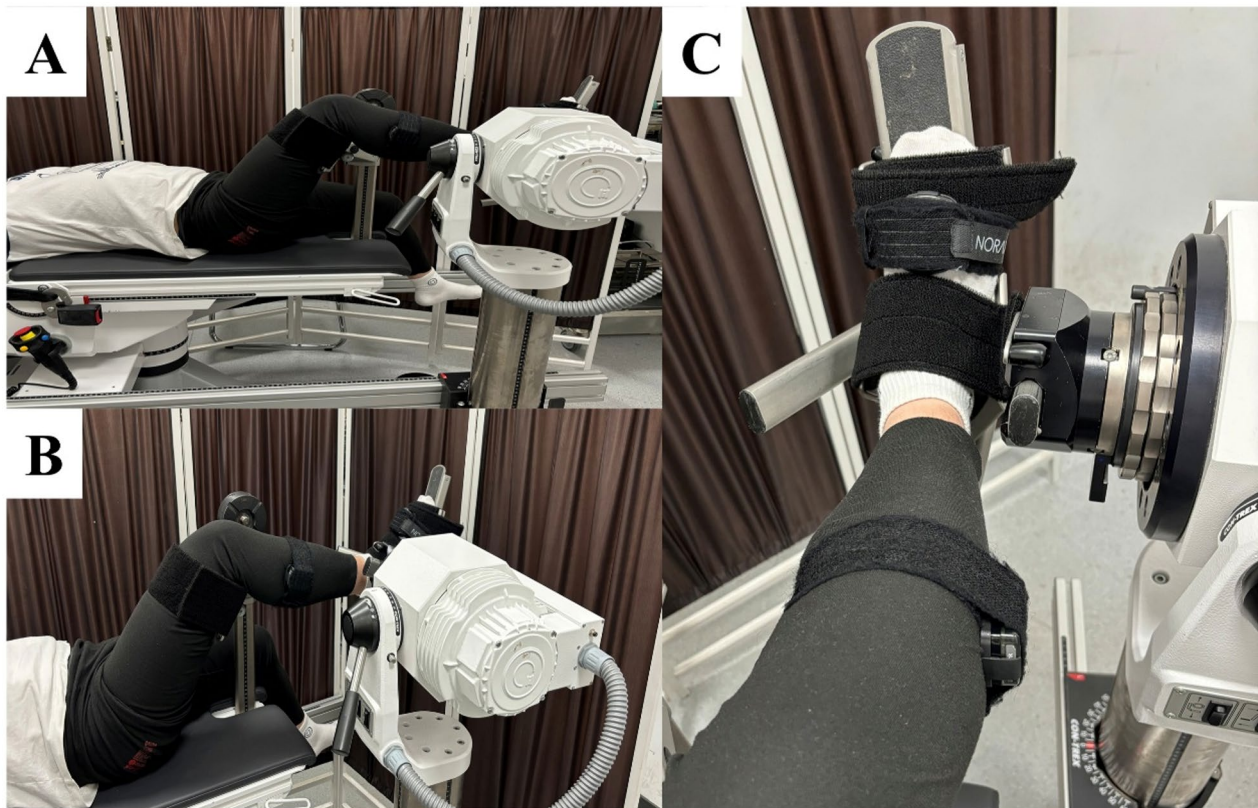


Fig. 1 Schematic of the experimental protocol. **A–B** Lateral view of the participant in the supine position with the knee stabilized by a restraining device. **C** Superior view showing IMU placement and details of the isokinetic dynamometer setup

direction consisted of three valid trials, separated by approximately 30 s. Trials with protocol violations (e.g., premature stop, discontinuous movement, or obvious compensatory movement) were discarded and immediately repeated once. During all aJPR tests, the foot was secured to the dynamometer footplate and the ankle was constrained to move predominantly in the intended plane (plantarflexion/dorsiflexion or inversion/eversion). The IMU sensors, attached to the distal tibia and dorsum of the foot, therefore recorded the three-dimensional orientations of these segments during the same constrained movements, rather than during fully free, unconstrained ankle motion.

Outcome measures

The primary outcome was the absolute error (AE, degrees) during aJPS: $|\text{reproduced angle} - \text{target angle}|$. AE was calculated separately for (i) the dynamometer (reference AE) and (ii) the IMU (sensor AE). For analysis, the mean AE from the three trials per direction per participant was used.

Sample size

Sample size estimation was performed using G*Power software (V3.1.9.2; Heinrich Heine University Düsseldorf, Germany). Preliminary data from 5 per group were used to estimate the effect size. For the independent samples t-test, with $\alpha = 0.05$, power $(1 - \beta) = 0.80$, and an estimated effect size = 1.09, an a priori power analysis indicated that a minimum total sample size of 30 would be required.

For intra-session reliability, sample size was planned to achieve prespecified precision of ICC estimates. Using Bonett's method (anticipated ICC = 0.80; $k = 3$; two-sided 95% CI half-width $\Delta\text{ICC} = 0.10$), the minimum required sample size was 36 participants [19].

For validity and agreement between instruments, acceptable error was prespecified (RMSE and/or Bland–Altman limits of agreement within $\pm 5\text{--}10^\circ$) [20–24]. Bland–Altman analyses were conducted with 53 paired observations per direction, and exact parametric 95% confidence intervals for the limits of agreement were computed according to Carkeet [25].

Statistical analysis

Analyses were conducted in SPSS 27.0 and GraphPad Prism 10 with two-tailed $\alpha = 0.05$.

Reliability

Test–retest reliability was quantified by ICC value of intra-session reliability. Interpretation: poor (< 0.50), moderate ($0.50–0.75$), good ($0.75–0.90$), excellent (> 0.90) [26]. The standard error of measurement ($SEM = SD \cdot \sqrt{1 - ICC}$) and minimal detectable change at 95% confidence ($MDC_{95} = 1.96 \cdot \sqrt{2} \cdot SEM$) were also calculated.

Agreement (IMU vs. dynamometer)

Bland–Altman analysis assessed bias (mean difference) and 95% limits of agreement ($LOA = bias \pm 1.96 \cdot SD$ of differences).

Between-group differences

Mean AE (per direction) was compared between CON and CAI. Normality was checked (Shapiro–Wilk). Paired-samples *t*-tests were used for normally distributed data with equal-variance checks; otherwise, Mann–Whitney U tests were applied.

Additional analyses

Based on CAIT scores, diagnostic utility was explored using receiver-operating characteristic (ROC) curves for IMU- and dynamometer-derived AE, reporting area under the curve (AUC), optimal cut-offs, sensitivity, specificity, positive/negative likelihood ratios, and predictive values.

The study flow is depicted in Fig. 2.

Results

Baseline data

There were no significant between-group differences in demographic data ($P > 0.05$). The only significant difference was that the CON group reported a higher physical activity level than the CAI group ($P = 0.015$; Table 1).

Intra-session reliability

Table 2 summarizes ICC, SEM, and MDC_{95} for three consecutive ankle JPS trials recorded by the isokinetic dynamometer and the IMU. Overall, both instruments exhibited good-to-excellent reliability ($ICC > 0.80$). The dynamometer demonstrated excellent reliability in plantarflexion ($ICC = 0.951$), dorsiflexion ($ICC = 0.955$), inversion ($ICC = 0.909$), and eversion ($ICC = 0.934$). The IMU showed excellent reliability in plantarflexion ($ICC = 0.903$) and good reliability in dorsiflexion ($ICC = 0.887$), inversion ($ICC = 0.882$), and eversion ($ICC = 0.829$). As expected, the IMU yielded larger SEM ($0.62–1.19$) and MDC_{95} ($1.72–3.29$) than the dynamometer ($SEM: 0.24–0.34$; $MDC_{95}: 0.66–0.94$), indicating greater measurement variability. Taken together, the IMU demonstrated acceptable intra-session reliability when benchmarked against the dynamometer (mean $ICC > 0.87$).

Concurrently validity and agreement

Bland–Altman plots of the agreement between the IMU and the isokinetic dynamometer are presented in Fig. 3. In the CON group, plantarflexion (Fig. 3A) showed a mean difference of $-0.40^\circ \pm 0.83^\circ$ (95% CI -0.35° to -0.27°) with 95% limits of agreement (LoA) from -1.67° to 1.58° . Dorsiflexion (Fig. 3B) showed a mean difference of $-1.58^\circ \pm 1.72^\circ$ (95% CI -2.22° to -0.94°) with LoA from -4.96° to 1.80° . Inversion (Fig. 3C) showed a mean difference of $-1.25^\circ \pm 2.07^\circ$ (95% CI -2.02° to -0.48°) with LoA from -5.29° to 2.81° . Eversion (Fig. 3D) showed a mean difference of $-1.40^\circ \pm 1.86^\circ$ (95% CI -2.09° to -0.71°) with LoA from -5.05° to 2.25° .

In the CAI group, plantarflexion (Fig. 3E) showed a mean difference of $-0.78^\circ \pm 2.02^\circ$ (95% CI -1.65° to 0.09°) with LoA from -4.74° to 3.18° . Dorsiflexion (Fig. 3F) showed a mean difference of $-2.09^\circ \pm 2.14^\circ$ (95% CI -3.02° to -1.16°) with LoA from -6.38° to 2.10° . Inversion (Fig. 3G) showed a mean difference of $-2.57^\circ \pm 2.14^\circ$ (95% CI -3.50° to -1.64°) with LoA from -6.76° to 1.61° . Eversion (Fig. 3H) showed a mean difference of $-2.39^\circ \pm 3.69^\circ$ (95% CI -3.99° to -0.79°) with LoA from -9.61° to 4.83° .

Between-group comparisons

Between-group findings are shown in Fig. 4. Dynamometer-derived AE was significantly greater in the CAI group than in controls for plantarflexion (Fig. 4A, $P = 0.001$, $ES = 0.96$, 95%CI = $1.26–2.33$), dorsiflexion (Fig. 4B, $P = 0.001$, $ES = 0.89$, 95%CI = $0.76–1.75$), and inversion (Fig. 4C, $P = 0.001$, $ES = 0.81$, 95%CI = $0.84–1.75$), with no significant difference in eversion (Fig. 4D, $P = 0.056$, $ES = 1.13$, 95%CI = $-0.02–1.24$). IMU-derived AE was significantly greater in CAI across all four directions—plantarflexion (Fig. 4E, $P = 0.001$, $ES = 1.32$, 95%CI = $1.84–3.31$), dorsiflexion (Fig. 4F, $P = 0.001$, $ES = 1.61$, 95%CI = $0.87–2.66$), inversion (Fig. 4G, $P = 0.001$, $ES = 2.05$, 95%CI = $1.48–3.76$), and eversion (Fig. 4H, $P = 0.019$, $ES = 2.39$, 95%CI = $0.27–2.93$)—suggesting higher sensitivity of the IMU to group differences, particularly for eversion.

Diagnostic utility

ROC analyses are summarized in Table 3; Fig. 5. For the dynamometer, plantarflexion showed excellent discrimination ($AUC = 0.933$, 95% CI: $0.829–0.983$, $P < 0.001$) with sensitivity 95.65% and specificity 76.67%. Dorsiflexion also performed well ($AUC = 0.878$, 95% CI: $0.758–0.951$, $P < 0.001$; sensitivity 86.96%, specificity 86.67%). Inversion demonstrated good diagnostic value ($AUC = 0.876$, 95% CI: $0.757–0.951$, $P < 0.001$) with high specificity (96.67%) and a strong positive likelihood ratio ($PLR = 20.87$). Eversion showed limited utility ($AUC = 0.670$, 95% CI: $0.528–0.793$, $P = 0.023$; sensitivity 69.57%, specificity 66.67%).

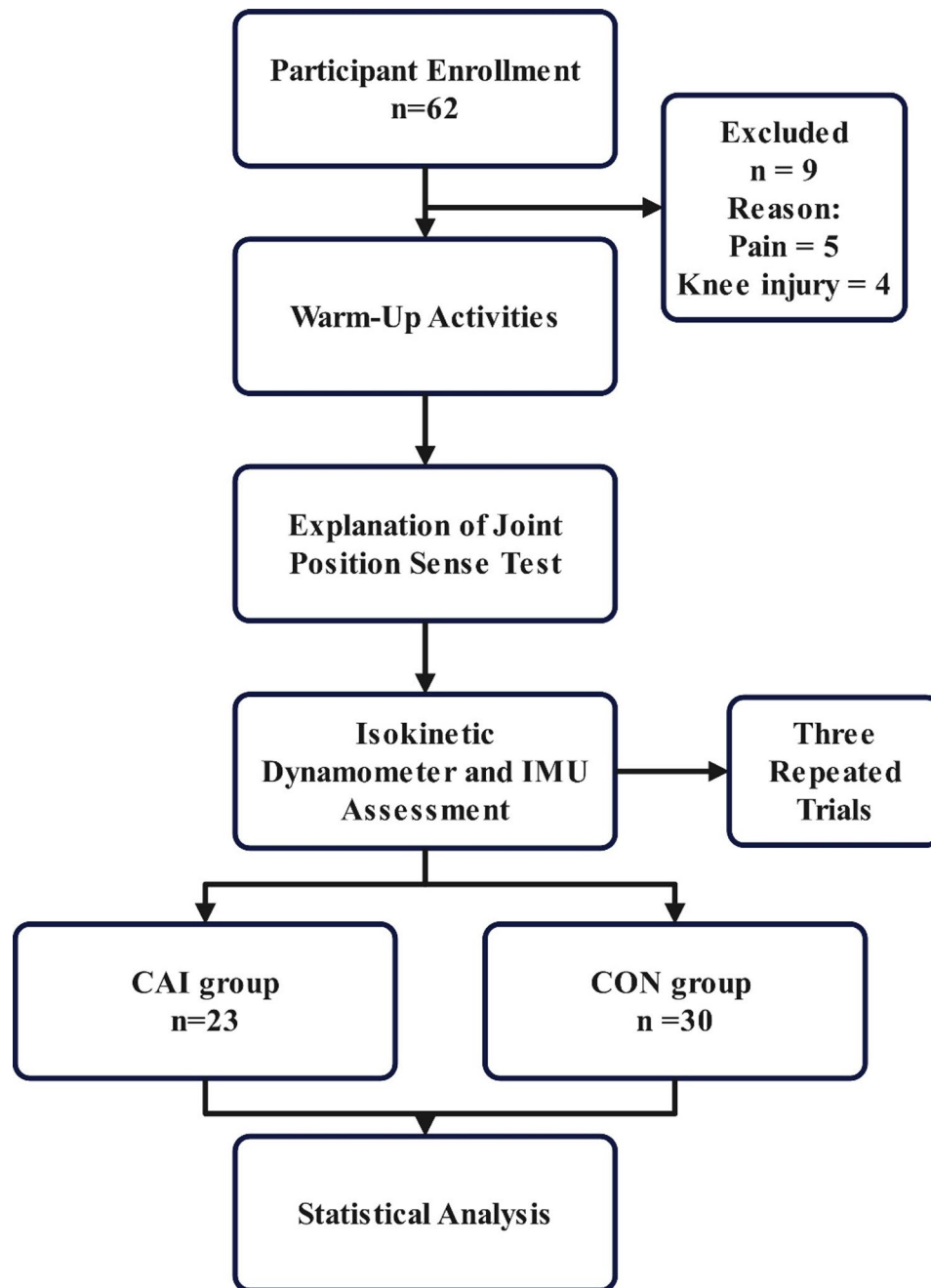


Fig. 2 Flowchart of the experimental procedure illustrating participant allocation and the overall study process. CAI: Chronic Ankle Instability; CON: Healthy Controls

Table 1 Baseline demographic characteristics of the CON and CAI groups

Index	CON	CAI	Effect Sizes	P-value
Age (years)	22.17 ± 2.85	21.61 ± 2.71	2.79	0.474
Sex (male/female)	15/15	14/9	0.11	0.43
Height (cm)	167.10 ± 10.95	169.17 ± 7.14	9.49	0.434
Weight (kg)	74.307 ± 10.22	74.261 ± 4.74	8.31	0.984
BMI (kg/m ²)	24.32 ± 2.27	25.14 ± 2.33	2.29	0.200
Physical activity level	5.88 ± 2.13	4.67 ± 1.02	1.74	0.015*

CON healthy control group, CAI chronic ankle instability

*: $P < 0.05$

Table 2 Intra-session reliability across three consecutive JPS

	Isokinetic Dynamometer				IMU			
	ICC	95%CI	SEM	MDC95	ICC	95%CI	SEM	MDC95
Plantarflexion	0.951	(0.923, 0.97)	0.30	0.84	0.903	0.846, 0.941	0.62	1.72
Dorsiflexion	0.955	(0.929, 0.972)	0.24	0.66	0.887	0.821, 0.931	0.67	1.87
Inversion	0.909	(0.856, 0.944)	0.34	0.94	0.882	0.813, 0.928	0.92	2.54
Eversion	0.934	(0.895, 0.959)	0.32	0.87	0.829	0.730, 0.896	1.19	3.29

JPS Joint Position Sense, MDC95 95% minimal detectable change, SEM standard error of measurement

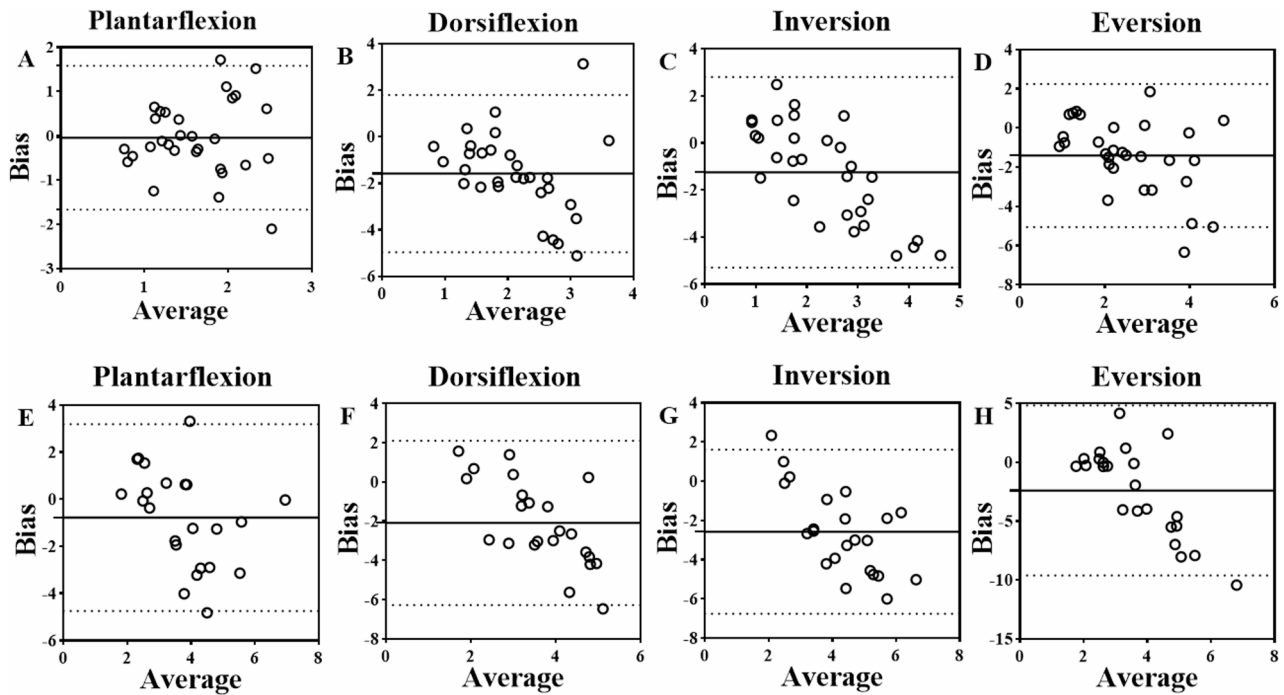


Fig. 3 A–D Agreement of the CON group in isokinetic dynamometer and IMU. E–H Agreement of the CAI group in isokinetic dynamometer and IMU

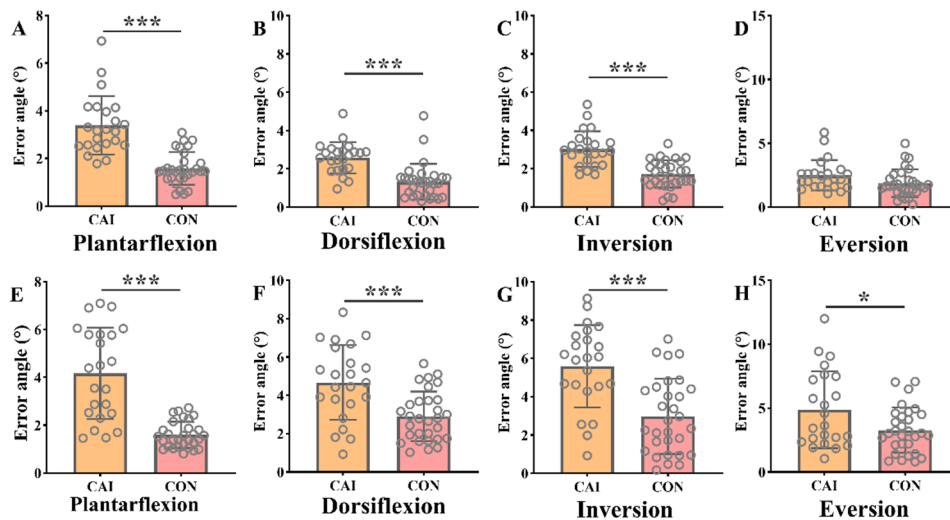


Fig. 4 A–D Between-group comparisons using the isokinetic dynamometer (CON vs. CAI). E–H Between-group comparisons using the IMU (CON vs. CAI)

Table 3 Diagnostic value of each index for chronic ankle instability

Index		AUC (95%CI)	Cut-off	Sensitivity	Specificity	PLR	NLR	PPV	NPV	P value
ID	Plantarflexion	0.933(0.829–0.983)	> 1.87	95.65	76.67	4.1	0.06	75.9	95.8	0.0001***
	Dorsiflexion	0.878(0.758–0.951)	> 1.75	86.96	86.67	6.52	0.15	83.3	89.7	0.0001***
	Inversion	0.876(0.757–0.951)	> 2.66	69.57	96.67	20.87	0.31	94.1	80.6	0.0001***
	Eversion	0.670(0.528–0.793)	> 1.81	69.57	66.67	2.09	0.46	61.5	74.1	.0234*
IMU	Plantarflexion	0.912(0.801–0.972)	> 2.73	69.57	100	NA	0.3	100	81.1	0.0001***
	Dorsiflexion	0.772(0.636–0.876)	> 0.376	73.91	80.00	3.7	0.33	73.9	80.0	0.0001***
	Inversion	0.812(0.681–0.906)	> 4.51	78.26	80.00	3.91	0.27	75.0	82.8	0.0001***
	Eversion	0.637(0.493–0.765)	> 7.08	30.43	100	NA	0.7	100	65.2	0.0887

ID Isokinetic Dynamometer, NA Missing Value, PLR positive likelihood ratios, NLR negative likelihood ratios, PPV positive predictive value, NPV negative predictive value

*, $P < 0.05$; ***, $P < 0.001$

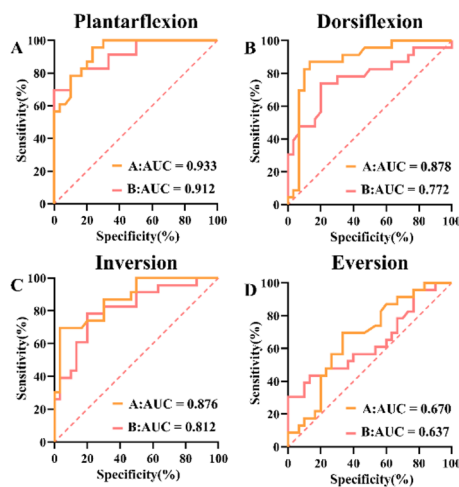


Fig. 5 ROC-based diagnostic performance of the isokinetic dynamometer (a) and IMU (b) for classifying ankle instability

The IMU followed a similar pattern, with plantarflexion yielding an AUC of 0.912 (95% CI: 0.801–0.972, $P < 0.001$) and 100% specificity at the optimal cut-off, despite lower sensitivity (69.57%). Dorsiflexion and inversion showed good discrimination (AUC = 0.772, 95% CI: 0.636–0.876, $P < 0.001$; and AUC = 0.812, 95% CI: 0.681–0.906, $P < 0.001$, respectively). Eversion provided the least diagnostic value (AUC = 0.637, 95% CI: 0.493–0.765, $P = 0.089$), not reaching statistical significance.

Discussion

The present study examined the intra-session reliability, concurrent validity, and diagnostic utility of a wearable IMU system for assessing ankle JPS in healthy individuals and those with CAI. The main findings were that (1) IMU-based aJPR measurements demonstrated good to excellent reliability across movement directions, comparable to an isokinetic dynamometer; (2) IMU-derived ankle angles showed small systematic bias and acceptable agreement with the dynamometer in both groups; and (3) individuals with CAI exhibited larger JPS errors than controls, particularly in plantarflexion, dorsiflexion, and

inversion, with IMU-based measures in these directions showing good discriminative ability for identifying CAI. Overall, the findings supported the study hypotheses, indicating that IMUs are a reliable and valid tool for ankle JPS assessment.

Reliability and advantages of IMU-based ankle JPS assessment

The isokinetic dynamometer showed excellent intra-session reliability, and IMU-based JPS measurements also demonstrated good to excellent reliability across all movement directions (ICCs = 0.83–0.90), only slightly lower than the dynamometer and unlikely to affect clinical interpretation. Previous studies using inertial sensors to assess proprioception of other joints have generally reported moderate to high reliability. For example, Rahlh et al. used IMUs to evaluate knee JPS and reported relatively low reliability for single measurements (ICC \approx 0.60), whereas averaging multiple trials was required to achieve satisfactory reliability and to distinguish younger from older adults [12]. By contrast, single-trial ICCs for IMU-based ankle JPS in the present study were already in the 0.8–0.9 range, and averaging three repetitions is likely to further increase reliability, indicating that IMUs can provide excellent reliability for ankle proprioception assessment.

Compared with other portable devices used to assess ankle JPS, these findings further underline the advantages of IMU-based measurements. High reliability with low measurement error was achieved with only three repetitions per condition, whereas simpler devices such as smartphones typically require more repetitions to reach acceptable levels. Chirumbolo reported that an ankle JPS ICC of 0.79 for a smartphone-based digital inclinometer was obtained only when ten repeated measurements were collected and the best eight were retained [13]. In contrast, satisfactory ICC values were achieved here with just three repetitions, which may reflect the IMU's resistance to magnetic interference, its compact form factor, and more standardized attachment and calibration

procedures, together enhancing measurement sensitivity and reproducibility.

However, within the present protocol, the slightly lower reliability of the IMU compared with the isokinetic dynamometer is likely related to the measurement principles of each system. The dynamometer quantifies joint angles via a rigid mechanical linkage, whereas the IMU sensors are attached to the skin and are more susceptible to soft-tissue artefact, subtle changes in sensor alignment, and sensor-fusion or calibration noise, all of which can increase trial-to-trial variability. These factors probably contributed to the larger SEM and MDC values observed for the IMU.

Concurrent validity of IMU-based ankle joint position sense measurements

Bland–Altman analysis showed good concurrent validity of the IMU against the isokinetic dynamometer in both CON and CAI groups. The IMU slightly overestimated ankle joint angles (mean differences $\approx -0.4^\circ$ to 2.6°), with limits of agreement mostly within $\pm 5^\circ$ in controls and up to $\sim \pm 7$ – 10° only for eversion, which is small relative to the physiological range of ankle motion. These error magnitudes are comparable to recent IMU validation studies of lower-limb kinematics, where biases of ~ 1 – 3° and RMSE or limits of agreement within ± 5 – 10° are generally considered acceptable when compared with optical motion capture or dynamometry [20–24].

Agreement was tighter for plantarflexion and dorsiflexion than for inversion and eversion, consistent with evidence that IMUs are more accurate in predominantly sagittal, single-plane movements and less accurate as multi-planar components increase [21, 22, 24]. The wider limits of agreement in the CAI group, particularly for frontal-plane motions, likely reflect greater trial-to-trial variability in joint position sense in individuals with chronic ankle instability, in line with reports of proprioceptive deficits in this population [1, 27, 28].

Clinically, these small biases and acceptable agreement support the use of IMU-based joint position measurements as a practical alternative to dynamometer-based assessments of ankle joint position sense when large equipment is unavailable [20, 21, 23]. However, concurrent validity was established under isokinetic, constrained motion that reduces multi-planar movement and sensor misalignment, so IMU performance in unrestricted functional tasks may be somewhat lower. Further studies should examine concurrent validity in more complex multi-planar activities and field settings.

Direction-specific impairments and diagnostic value of ankle JPS in CAI

CAI exhibited greater aJPR errors in plantarflexion, dorsiflexion, and inversion. These findings are consistent with

the systematic review by Xue et al., which confirmed that individuals with CAI have impaired ankle proprioception, including both kinesthesia and joint position sense [1]. Our results showed a similar pattern, with particularly pronounced inversion JPS errors in CAI, consistent with post-injury damage to periarticular mechanoreceptors and subsequent reductions in proprioceptive acuity in this plane [2, 29]. Given that inversion is the most common mechanism of ankle sprain, these results further reinforce the presence of proprioceptive impairment following injury.

The diagnostic utility of ankle JPS testing for identifying CAI was also examined. Whether assessed with an isokinetic dynamometer or an IMU, aJPR tests in plantarflexion and dorsiflexion demonstrated high sensitivity and specificity, with plantarflexion showing the strongest discriminative power (AUC: dynamometer 0.93; IMU 0.91). Most lateral ankle sprains occur with the ankle in plantarflexion, during which the anterior and lateral soft tissues act as passive restraints. Proprioceptive receptors such as muscle spindles and Ruffini endings, which are abundant in muscles, joint capsules, and ligaments [2, 29], are therefore vulnerable to injury, and their capacity to encode and transmit joint position information may be compromised these receptors may also be damaged when soft tissue injury occurs. The information acquisition and transmission capacity of muscle spindles and Ruffini endings may be impaired [30, 31]. Classic work has identified these receptors as primary contributors to JPS [2]; under visual occlusion in a plantarflexed posture, impaired afferent input from these structures likely underlies the larger aJPR errors observed in CAI. Recent studies have reported comparable findings [1, 16].

By contrast, the diagnostic utility of eversion was relatively low. For IMU-based measurements, the AUC was 0.64 and did not reach statistical significance, reflecting high variability and substantial overlap between groups. Although mean eversion errors differed significantly between CAI and controls, the clinical discriminative value of eversion appears limited. Plantarflexion, dorsiflexion, and inversion showed greater clinical relevance: ROC analyses indicated that IMU-measured plantarflexion errors exceeding approximately 2.7° identified ankle instability with 100% sensitivity, whereas inversion errors exceeding approximately 4.5° corresponded to $\sim 80\%$ specificity. Clinically, abnormally large aJPR errors in these directions can therefore be interpreted as indicative of proprioceptive deficits and may aid in screening individuals at risk of functional ankle instability.

Clinical implications and role of IMUs in practice

The findings of this study have clear clinical implications. Proprioceptive assessment can help clinicians—including therapists and athletic trainers—identify deficits

promptly [1, 32]. By quantifying aJPR errors, individuals with sensorimotor control impairments can be recognized before functional instability becomes clinically apparent, enabling targeted preventive training [33–35]. Previous studies have shown that targeted proprioceptive training can effectively improve JPS in CAI [36]. However, due to the lack of reliable and convenient assessment tools, routine clinical proprioception testing is rarely performed [37]. IMU systems are inexpensive, compact, easy to operate, and yield readily interpretable results, making them well suited to clinical practice, particularly in resource-limited settings such as primary care hospitals and rehabilitation clinics.

Limitation

This study has several limitations. Reliability was evaluated within a single session only, so the results primarily reflect short-term intra-session repeatability rather than true test–retest reliability; future work should adopt multi-session designs to examine longer-term stability. In addition, only active JPR tasks were used, and the inclusion of passive reproduction tasks in subsequent studies would help to further clarify the applicability of IMU-based assessment. Reliability and concurrent validity were established under isokinetic, constrained joint motion with the ankle fixed to footplate, a setup that likely reduced multi-planar motion and soft-tissue artefact and may therefore underestimate measurement variability. At the same time, these controlled conditions closely mirror many clinical and applied contexts that use devices with a constrained joint axis, and our findings provide supportive evidence for integrating IMUs into such portable systems—particularly in outpatient or team-sport settings—to quantify joint motion and joint position sense. Generalization of the present results to less controlled, field-based environments should nevertheless be made with caution, and future studies are needed to confirm IMU performance in more dynamic, multi-planar functional tasks.

Conclusion

This study demonstrated that a research-grade IMU provides ankle joint position sense measurements with good intra-session reliability and acceptable agreement with an isokinetic dynamometer in both healthy individuals and those with chronic ankle instability. IMU-derived angles showed small systematic underestimation and relatively narrow limits of agreement, supporting its concurrent validity for constrained, isokinetic ankle JPS assessment. Participants with chronic ankle instability exhibited larger JPS errors than controls, particularly in plantarflexion, dorsiflexion, and inversion. Overall, these findings suggest that IMU-based ankle JPS assessment, especially in plantarflexion and inversion, may serve as a

feasible tool for screening and monitoring proprioceptive deficits in clinical and sports rehabilitation settings.

Abbreviations

CAI	Chronic Ankle Instability
IMU	Inertial Measurement Units
JPS	Joint Position Sense
AE	Absolute Error
ROC	Receiver-Operating Characteristic
AUC	Area Under the Curve
JPR	Joint Position Reproduction
aJPR	Active Joint Position Reproduction
aJPS	Active Joint Position Sense

Acknowledgements

The author would like to express gratitude to all participants in this study, particularly those in the CAI group.

Authors' contributions

All authors contributed to the study conception and design. S.W, Y.N, and X.Z conceptualized the study, gathered and analyzed the data, and drafted the manuscript; C.W, W.C, and Q.W participated in the study design and performed the device; G.H, H. L, and J.L oversaw participant inclusion; N.M conceived the study design, revised the manuscript, and reviewed both the initial and final drafts. Each author contributed to the article and approved the manuscript for submission in its entirety.

Funding

This research was supported by Special Program for Medical and Health Talents of Jilin Province (No. 2024WSZX-B10), Jilin Provincial Science and Technology Development Plan Project (No. 20240602084RC), and independent innovation fund project of Jilin Sports University (No. 2023004Z).

Data availability

Data are available under reasonable request to the corresponding author.

Declarations

Ethics approval and consent to participate

The study was conducted in accordance with the ethical principles of the World Medical Association's Declaration of Helsinki and the Council for International Organizations of Medical Sciences (CIOMS) International Ethical Guidelines for Health-related Research Involving Humans. It was approved by the Ethics Committee of Jilin Sport University (approval No. 2025014), and written informed consent was obtained from all participants or their parents.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Received: 6 October 2025 / Accepted: 8 January 2026

Published online: 19 January 2026

References

1. X X, M T, L Q, S Y, H Y. Chronic ankle instability is associated with proprioception deficits: a systematic review and meta-analysis. *J Sport Health Sci.* 2021;10. <https://doi.org/10.1016/j.jshs.2020.09.014>.

2. Proske U, Gandevia SC. The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. *Physiol Rev*. 2012;92:1651–97. <https://doi.org/10.1152/physrev.00048.2011>.
3. JW, P B, G W, R A. Intrinsic functional deficits associated with increased risk of ankle injuries: a systematic review with meta-analysis. *Br J Sports Med*. 2012;46. <https://doi.org/10.1136/bjsports-2011-090137>.
4. Han J, Waddington G, Adams R, Anson J, Liu Y. Assessing proprioception: A critical review of methods. *J Sport Health Sci*. 2016;5:80–90. <https://doi.org/10.1016/j.jshs.2014.10.004>.
5. Shamsi M, Mirzaei M, Khabiri SS. Universal goniometer and electro-goniometer intra-examiner reliability in measuring the knee range of motion during active knee extension test in patients with chronic low back pain with short hamstring muscle. *BMC Sports Sci Med Rehabilitation*. 2019;11:4. <https://doi.org/10.1186/s13102-019-0116-x>.
6. Zöger M, Nimmerichter A, Baca A, Wirth K. Reproducibility of peak force for isometric and isokinetic multi-joint leg extension exercise. *BMC Sports Sci Med Rehabilitation*. 2025;17:14. <https://doi.org/10.1186/s13102-025-01061-1>.
7. Yang Q-H, Wang X-Q. Lumbar joint position sense measurement of patients with low back pain. *EFORT Open Reviews*. 2023. <https://doi.org/10.1530/EO-R-23-0077>.
8. Relph N, Herrington L. Criterion-Related validity of knee Joint-Position-Sense measurement using image capture and isokinetic dynamometry. *J Sport Rehabilitation*. 2015. <https://doi.org/10.1123/jsr.2013-0119>.
9. Nijmeijer EM, Heuvelmans P, Bolt R, Gokeler A, Otten E, Benjaminse A. Concurrent validation of the Xsens IMU system of lower-body kinematics in jump-landing and change-of-direction tasks. *J Biomech*. 2023;154:111637. <https://doi.org/10.1016/j.jbiomech.2023.111637>.
10. Wang J, Xu F, Zhang H, Wang B, Deng T, Zhou Z, et al. Validity of an inertial measurement system to measure lower-limb kinematics in patients with hip and knee pathology. *J Biomech*. 2025;178:112446. <https://doi.org/10.1016/j.jbiomech.2024.112446>.
11. Wang J, Wang R, Zhao P, Han T, Cui X, He Y, et al. The reliability and validity of a novel wearable inertial sensor to measure the cervical proprioception. *Med Eng Phys*. 2024;125:104125. <https://doi.org/10.1016/j.medengphy.2024.104125>.
12. Rahlf AL, Petersen E, Rehwinkel D, Zech A, Hamacher D. Validity and reliability of an inertial sensor-based knee proprioception test in younger vs. Older adults. *Front Sports Act Living*. 2019;1. <https://doi.org/10.3389/fspor.2019.00027>.
13. Chirumbole SG, Teater RH, Bals MM, Richie DR, Monfort SM, Chaudhari AMW. Assessing the reliability of a digital inclinometer app for measuring hip, knee, and ankle proprioception. *PLoS ONE*. 2024;19:e0308737. <https://doi.org/10.1371/journal.pone.0308737>.
14. Lee D, Han S. Validation of joint position sense of Dorsi-Plantar flexion of ankle measurements using a smartphone. *Healthc Inf Res*. 2017;23:183–8. <https://doi.org/10.4258/hir.2017.23.3.183>.
15. Almeida JRG, Monteiro LCP, de Souza PHC, dos Santos Cabral A, de Bergamo A et al. Athayde Costa e Silva A., Comparison of joint position sense measured by inertial sensors embedded in portable digital devices with different masses. *Front Neurosci*. 2025;19. <https://doi.org/10.3389/fnins.2025.1561241>.
16. Mei N, Jiang Z, Kurokawa H, Ueno Y, Liu H, Zou J, et al. Recurrent sprains of chronic ankle instability with chronic syndesmotic injury are primarily correlated with plantarflexion instability and multisensory deficits. *Phys Ther Sport*. 2025;73:77–85. <https://doi.org/10.1016/j.ptsp.2025.03.004>.
17. Hiller CE, Refshauge KM, Bundy AC, Herbert RD, Kilbreath SL. The Cumberland ankle instability tool: a report of validity and reliability testing. *Arch Phys Med Rehabil*. 2006;87:1235–41.
18. Alawna M, Unver B, Yuksel E. Effect of ankle taping and bandaging on balance and proprioception among healthy volunteers. *Sport Sci Health*. 2021;17:665–76. <https://doi.org/10.1007/s11332-020-00730-7>.
19. Dg B. Sample size requirements for estimating intraclass correlations with desired precision. *Stat Med*. 2002;21. <https://doi.org/10.1002/sim.1108>.
20. Bissenov A, Zhubi E, Engh MA, Gresits O, Tóth R, Terebessy T. Concurrent validity of wearable IMUs for sagittal plane lower-limb range of motion during walking and estimated ground reaction forces: a systematic review and meta-analysis. *J Orthop Surg Res*. 2025;20:891. <https://doi.org/10.1186/s13018-025-06322-w>.
21. Kim BH, Hong SH, Oh IW, Lee YW, Kee IH, Lee SY. Measurement of ankle joint movements using IMUs during running. *Sens (Basel)*. 2021;21:4240. <https://doi.org/10.3390/s21124240>.
22. Poitras I, Dupuis F, Biemann M, Campeau-Lecours A, Mercier C, Bouyer LJ, et al. Validity and reliability of wearable sensors for joint angle estimation: A systematic review. *Sens (Basel)*. 2019;19:1555. <https://doi.org/10.3390/s19071555>.
23. Seel T, Raisch J, Schauer T. IMU-based joint angle measurement for gait analysis. *Sens (Basel)*. 2014;14:6891–909. <https://doi.org/10.3390/s140406891>.
24. Teufl W, Miezal M, Taetz B, Fröhlich M, Bleser G. Validity of inertial sensor based 3D joint kinematics of static and dynamic sport and physiotherapy specific movements. *PLoS ONE*. 2019;14:e0213064. <https://doi.org/10.1371/journal.pone.0213064>.
25. Carkeet A. Exact parametric confidence intervals for Bland-Altman limits of agreement. *Optom Vis Sci*. 2015;92:e71–80. <https://doi.org/10.1097/OPX.0000000000000513>.
26. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*. 2016;15:155–63. <https://doi.org/10.1016/j.jcm.2016.02.012>.
27. Witchalls J, Waddington G, Blanch P, Adams R. Ankle instability effects on joint position sense when stepping across the active movement extent discrimination apparatus. *J Athl Train*. 2012;47:627–34. <https://doi.org/10.4085/1062-6050-47.6.12>.
28. X X. Do exercise therapies restore the deficits of joint position sense in patients with chronic ankle instability? A systematic review and meta-analysis. *Sports Med Health Sci*. 2023;5. <https://doi.org/10.1016/j.smhs.2023.01.001>.
29. Goodwin GM, McCloskey DI, Matthews PB. Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception? *Science*. 1972;175:1382–4. <https://doi.org/10.1126/science.175.4028.1382>.
30. Bali K, Dhillion MS, Vasistha RK, Kakkar N, Chana R, Prabhakar S. Efficacy of Immunohistological methods in detecting functionally viable mechanoreceptors in the remnant stumps of injured anterior cruciate ligaments and its clinical importance. *Knee Surg Sports Traumatol Arthrosc*. 2012;20:75–80. <https://doi.org/10.1007/s00167-011-1526-9>.
31. Wu X, Song W, Zheng C, Zhou S, Bai S. Morphological study of mechanoreceptors in collateral ligaments of the ankle joint. *J Orthop Surg Res*. 2015;10:92. <https://doi.org/10.1186/s13018-015-0215-7>.
32. Clark NC. Sensorimotor control of functional joint stability: scientific concepts, clinical considerations, and the articulo-neuromuscular cascade paradigm in peripheral joint injury. *Musculoskelet Sci Pract*. 2024;74:103198. <https://doi.org/10.1016/j.msksp.2024.103198>.
33. Jebreen M, Maffulli N, Migliorini F, Arumugam A. Known-group validity of passive knee joint position sense: a comparison between individuals with unilateral anterior cruciate ligament reconstruction and healthy controls. *J Orthop Surg Res*. 2023;18:525. <https://doi.org/10.1186/s13018-023-03996-y>.
34. Morris A, Fino NF, Pelo R, Cushman DM, Monson NE, Jameson T, et al. Reactive postural responses predict risk for acute musculoskeletal injury in collegiate athletes. *J Sci Med Sport*. 2023;26:114–9. <https://doi.org/10.1016/j.jsams.2023.01.003>.
35. Darbandi SM, Zarei M, Mohammadi H, Hosseinzadeh M. Investigating the value of balance and proprioception scores to predict lower limb injuries in professional judokas. *Sci Rep*. 2023;13:21726. <https://doi.org/10.1038/s41598-023-49114-0>.
36. McKeon PO, Ingersoll CD, Kerrigan DC, Saliba E, Bennett BC, Hertel J. Balance training improves function and postural control in those with chronic ankle instability. *Med Sci Sports Exerc*. 2008;40:1810–9. <https://doi.org/10.1249/MSS.0b013e31817e0f92>.
37. Mei N, Jiang Z, Zhong Z, Fu L, Hao J, Li Z, et al. Modified stabilization test to diagnose chronic syndesmotic injuries based on posture control. *Foot Ankle Int*. 2023;44:1034–43. <https://doi.org/10.1177/10711007231189713>.

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