Inertial sensors-based assessment to detect hallmarks of chronic ankle instability during single-leg standing: Is the healthy limb “healthy”?

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ABSTRACT

Background: Chronic ankle instability can be common in sportsmen and can increase the risk of damaging the articular surfaces and result in negative consequences to joint health. Balance assessment is often used to evaluate ankle instability characteristics and guide rehabilitation protocols. This study aims to investigate balance-related parameters in people with chronic ankle instability and healthy-matched controls, using inertial sensors.

Methods: Ten young adults with a history of multiple ankle sprains (30 y, 25–34, 5 females) and ten matched healthy controls (30 y, 23–39, 5 females) were invited to participate in the study. Inertial sensors were placed on the head of the astragalus and on the chest to collect kinematic parameters during a 20-s single-leg stance performed on the leg with ankle instability (and corresponding for the healthy controls) and on the contralateral leg, randomly. Outcomes were calculated with MATLAB and subsequently analyzed.

Findings: A significant group effect was found only for the inversion angle ($F_{1,15} = 12.514$, $p = 0.003$, $p\eta^2 = 0.455$), consisting of individuals with ankle instability being characterized by higher inversion angles (4.999 degrees, 95% CI: 1.987–8.011, p = 0.003) without significant side differences. No significant side x group effects were found for the assessed parameters.

Interpretation: Results from this study suggest that young adults with chronic ankle instability might be characterized by worse single-stance control in terms of inversion angle, and such worse performance could also be found in the contralateral leg. As such, inertial sensors could be used to assess kinematic parameters during balance tasks in people with chronic ankle instability.

1. Introduction

Chronic ankle instability (CAI) can be associated with frequent sprains, pain, and instability, impairing joint health (Brown and Mynark, 2007). Ankle sprains are among the most common lower extremity injuries, especially in sports players who participate in soccer, basketball, and volleyball (Fong et al., 2007), and are represented by inversion injuries that damage the lateral ligaments of the ankle (Willems et al., 2002). CAI is commonly characterized by a deficit in sensorimotor function, therefore affecting postural balance, proprioception and neuromuscular reflexes (Hertel and Corbett, 2019; Koshino et al., 2023), and higher-level adaptative neuromuscular responses to compensate for these deficits (Kim et al., 2022). Ankle joint instability could therefore increase the risk of damaging the articular surfaces and result in negative consequences to joint health (Brown and Mynark, 2007; Hintermann et al., 2002).

Static balance assessment is often recommended and useful to support the “return to sports activities” decision (Martin et al., 2021; Wikstrom et al., 2020). Despite some limitations, as dynamic balance may better reflect the sensorimotor control mechanisms required in sport-specific tasks, poor balance during single-leg stance has been suggested to predict a higher risk for ankle sprains (Trojian and McKeag, 2006).

The assessment of balance during monopodalic stance could help to

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identify alterations in people with CAI, with some authors reporting mixed results when comparing the affected limb with the "healthy" contralateral limb (Bernier et al., 1997; Brown and Mynark, 2007; Nakagawa and Hoffman, 2004; Ross et al., 2005; Ross and Guskiewicz, 2004; Yoshida and Suzuki, 2020). The non-uniformity of findings about balance alterations in the affected limb compared to the contralateral limb might be explained by the spontaneous self-organization of the sensorimotor system, consisting of "alterations in central programming at the spinal level" (Hertel and Corbett, 2019; Konradsen et al., 1997). Indeed, the"bilateral consequences of unilateral injury" hypothesis suggests that a general reorganization of the sensorimotor system may occur in ankle injuries, and therefore it might present in people with CAI (Gauffin et al., 1988; Waddington and Adams, 1999).

Personalized technology solutions, including advanced wearable devices, should be implemented and can support the assessment and self-empowerment of chronic patients (Lasorsa et al., 2016). Inertial sensors are portable and cheap, and have been suggested to be easily applicable in clinical practice (Parel et al., 2012) as they can provide reliable quantitative measures of range of motion (RoM) and balance in individuals with CAI (Abdo et al., 2020; Chiu et al., 2017; Gómez-Espinosa et al., 2018; Koshino et al., 2023). As such, the aim of this study was to assess RoM and balance parameters in individuals with CAI, comparing the affected and the contralateral limb to individuals without previous history of ankle sprains and instability. According to the literature and the previous hypothesis on bilateral effects of unilateral injuries, it might be expected to find altered balance-related parameters in both the CAI and contralateral leg, compared to healthy controls.

2. Methods

Participants were recruited from local sports clubs who met the inclusion criteria and volunteered to participate in this study. The selection criteria for patients with chronic ankle instability from the International Ankle Consortium were considered (Gribble et al., 2014), including participants from both sexes, aged between 18 and 50 y, with a previous history of multiple ankle sprains, the initial sprain occurring >1 year before the study and with the last event occurring during in the last 12 months but not earlier than 3 months before the evaluation. No subject was receiving physical therapy treatment for any lower extremity injuries. Participants were excluded if they presented a history of fractures, severe traumas or surgery to lower limbs, a history of epilepsy or other neurological diseases, other clinical conditions or drugs affecting balance, or if they reported a sprain within 3 months before the test. The Italian version of the Cumberland Ankle Instability Tool (CAIT-I) was also administered, and participants were excluded if they presented a score > 24 (Contri et al., 2023). The frequency of episodes of injured ankle joint "giving way" and "recurrent sprains" was also collected, and participants had to report at least 2 episodes of 'giving way' in the 6 months prior to the study enrolment and two or more sprains to the same ankle (Delahunt et al., 2010; Gribble et al., 2014). A matched-control sample was selected according to age, sex, and limb dominance distribution. The dominant limb was defined as the limb used in at least 2 of the 3 following tests: recovering balance after a posterior push, stepping up onto a box, and kicking a ball with maximal accuracy through a goal (Hoffman et al., 1998). Assessments were performed between April and December 2022 in a University Hospital's School of Physiotherapy laboratory. All the participants were informed about the study procedures and were asked to sign the informed consent prior to participating in the study. All procedures were performed according to the principles of the Declaration of Helsinki and were approved by the ethical committee of the University of Trieste (122/2022).

2.1. Procedures

Participants presented to the assessment at least 48 h after their last training and in the absence of pain, fatigue, or discomfort. They were also asked to refrain from caffeine or smoking for at least 2 h before testing. Female athletes were tested during the follicular phase of the menstrual cycle. After arrival at the laboratory, they were again instructed about the procedures and some anthropometric and demographic data were collected. Body mass and height were measured with a scale and a stadiometer. After positioning the inertial sensors, participants were asked to stand on a single leg, eyes open, with their hands on the hips and asked to put the lifted foot midway between the knee and the floor. The stance was maintained for at least 20 s and parameters were analyzed between the 5th and 15th second of the test. Participants were familiarized with the required stance 2 times and data were collected from the third trial. The test was performed on the affected limb (and the corresponding leg in the control group according to dominance), and on the contralateral limb, following a randomized order based on tossing a coin before the test.

2.1.1. Inertial sensors-based assessment

Four wireless IMU sensors (MTw sensors, Xsens Technologies BV, Netherlands) were applied to acquire the kinematic signals during the single leg stance test. The sensors were placed on the head of the astragalus and at sternal level and were fixed with a body strap. Each MTw sensor unit contains a 3D-gyroscope, accelerometer and magnetometer, which together provide the orientation of the technical coordinate system of the MTw relative to a global, earth-based coordinate system. The sampling frequency was 100 Hz. The variation of the Euler angles during the task was calculated by the dedicated vendor software, and then were exported for the offline analysis performed by MATLAB scripts. The rotations around the three axes (roll, pitch and yaw) were measured as a relative measurement with respect to the initial reference position during the 20 s test in which the subject took his hands off the support and placed them on his hips. To evaluate the inversion and eversion movements the variations of the angle of Roll relative to the sensor placed on the head of the talus were measured and analyzed. We quantified the inversion and eversion movements by analysis of the roll angles. The following parameters were extracted: maximum foot inversion angle (°); maximum foot eversion angle (°); percentage of time spent in inversion (%); percentage of time spent in eversion (%); center of gravity of the foot (°), calculated as the average angle of inclination of the foot with respect to the starting position; frequency of foot oscillations, calculated considering the peaks with variation of at least one degree (Hz); chest swing range (°); center of gravity of the chest, intended as the average angle of inclination of the chest with respect to the starting position (°).

2.2. Statistical analysis

All statistical analyses were performed with the SPSS v.22 (IBM inc.) software. Shapiro-Wilk test for normality of distribution was performed. Data are reported as the medians and 25th–75th percentile or counts and proportions (%) as appropriate. A mixed-factors analysis of variance (ANOVA) with between-subjects (group: CAI vs healthy controls) and within-subjects (side: affected ankle/corresponding vs contralateral ankle) effects was performed. In case of significant main effects, Tukey's post-hoc tests were performed. Partial eta square ($p\eta^2$) was chosen as measure of effect size. Statistical significance was set at $p < 0.05$ for all statistical analyses.

3. Results

Ten participants with CAI (30 y, 25–34, 5 females) and 10 matched healthy controls (30 y, 23–39, 5 females) were included in the study. No significant differences were present in demographics and anthropometrics. (Table 1). The affected ankle in the CAI group was the dominant limb in 8/10 of the participants, and the corresponding dominance was chosen for 8/10 of the healthy controls. Participants in the CAI group reported a mean of 4 (range 2–5) episodes of “giving way” in the 6 months prior to the study enrolment, and 3 (range 2–4) episodes of recurrent sprain, and presented a CAIT-I score of 19.5 ± 2.6.

Inertial sensors analysis showed no significant side x group effects for the assessed measures (Table 2). A significant side difference was found only for chest CoG ($F_{1,15} = 7.356$, $P = 0.016$, $p\eta^2 = 0.329$), presenting larger oscillations during the monopodalic stance on the affected/corresponding limb (3.518, 95% CI: 0.753–6.283, $P = 0.016$). A significant group effect was found only for the inversion angle ($F_{1,15} = 12.514$, $P = 0.003$, $p\eta^2 = 0.455$), consisting in individuals with CAI being characterized by higher inversion angles (4.999 degrees, 95% CI: 1.987–8.011, $P = 0.003$) (Fig. 1).

4. Discussion

The findings from this study confirm the application of inertial sensor-based assessments to detect postural abnormalities during single-leg stance in people with CAI. In particular, these results suggest that individuals with CAI might be characterized by increased inversion angle compared to matched healthy controls; nevertheless, such impaired stabilization was found in both ankles, therefore suggesting that compared to controls, individuals with CAI might present lower control over the ankle joint also in the limb without previous history of repeated ankle sprains. This finding also confirms the previous ‘bilateral consequences of unilateral injury’ hypothesis (Gauffin et al., 1988; Waddington and Adams, 1999), in which unilateral injury could lead to bilateral consequences due to a general reorganization of the sensorimotor system, and this might be observed as an altered postural control during a single-leg stance on the “healthy“limb. The reported deficits in inversion/eversion angles are in line with previous literature suggesting these parameters being altered in CAI compared to healthy controls and the contralateral leg (Abdel-Aziem and Draz, 2014; Xue et al., 2021); nevertheless, we reported a significant group effect only for the inversion angle, without observing significant differences between the affected and the contralateral ankle. The inconsistency of the results might be explained due to the different testing protocols provided in the literature, ranging from the more static/postural tasks to dynamic tasks such as jumping and landing (Xu et al., 2022; Ziaei Ziabari et al., 2022), and therefore they should be cautiously considered according to the specific task. During single-leg stance it has been suggested that higher sagittal and vertical perturbations might be present on the sprained side compared to the non-sprained side, whereas no significant differences were reported in the lateral-horizontal direction (Yoshida and Suzuki, 2020).

Table 1
Demographic, anthropometrics, and clinical characteristics of the included sample. Medians (25th–75th percentile) and proportions.

	CON *n* = 10	CAI *N* = 10	Significance
Age (y)	30 (25–34)	30 (23–39)	0.739
Sex - females [n (%)]	5 (50)	5 (50)	1.000
Body mass (kg)	61.5 (59.0–71.5)	64.5 (57.8–73.5)	0.774
Body height (m)	1.69 (1.64–1.76)	1.70 (1.65–1.79)	0.936
History of CAI (y)		4.2 (2.6–7.1)	
Time from last ankle sprain (days)		189 (134–255)	

Notes: CON: healthy matched controls; CAI: chronic ankle instability. Bold values for p < 0.05 at the Mann-Whitney *U* test.

Table 2
Inertial units assessed parameters during single leg stance. Medians (25th–75th percentile).

	CON n = 10	CAI N = 10	Significance *group difference*
Maximum Inversion angle (°)			**0.003**
affected/corresponding	5.3 (4.1–6.2)	11.7 (6.6–13.9)	
contralateral	4.2 (3.1–5.2)	10.4 (6.5–11.7)	
Maximum Eversion angle (°)			0.222
affected/corresponding	1.3 (1.7–2.6)	6.5 (3.3–8.8)	
contralateral	2.9 (2.3–6.1)	3.7 (0.9–6.3)	
Perc. of time spent in inversion (%)			0.320
affected/corresponding	73.9 (52.8–81.3)	69.8 (56.5–77.6)	
contralateral	51.7 (24.7–74.8)	72.4 (35.3–96.6)	
Perc. of time spent in eversion (%)			0.316
affected/corresponding	26.1 (21.2–47.2)	30.2 (22.4–43.5)	
contralateral	46.8 (25.2–75.3)	27.6 (3.4–64.7)	
CoG of the foot (°)			0.069
affected/corresponding	−0.9 (−1.1–0.1)	−2.2 (−3.3 - -1.0)	
contralateral	−0.4 (−1.5–1.5)	−2.2 (−5.9–0.5)	
Frequency of foot oscillations (Hz)			0.107
affected/corresponding	0.8 (0.4–1.1)	1.2 (0.9–1.2)	
contralateral	0.8 (0.5–1.0)	0.8 (0.4–1.1)	
Chest swing range – inversion (°)			0.656
affected/corresponding	2.6 (1.3–3.8)	1.4 (0.5–2.9)	
contralateral	3.6 (1.5–9.5)	3.4 (1.6–5.7)	
Chest swing range – eversion (°)			0.359
affected/corresponding	4.6 (2.8–9.3)	9.3 (6.9–17.6)	
contralateral	7.6 (1.3–13.2)	5.2 (2.6–9.4)	
CoG chest (°)			0.203
affected/corresponding	2.2 (0.5–4.4)	4.4 (3.9–5.8)	
contralateral	1.0 (−5.3–4.3)	0.6 (−2.7–3.5)	

Notes: CON: healthy matched controls; CAI: chronic ankle instability. CoG: center of gravity. Bold values for p < 0.05 at the mixed-factors ANOVA (side; group) group main effect.

5. Conclusions

The use of inertial sensors to detect biomechanical alteration in people with CAI has been suggested to be useful and could easily provide a quantitative assessment of the perturbations associated with different static and dynamic tasks. Nevertheless, the different outcomes should be carefully considered according to the investigated task, and caution is warranted when comparing the sprained side with the contralateral as a measure of the impairment, as some parameters might be equally abnormal in the non-sprained side according to the suggested general reorganization of the sensorimotor system.

Compliance with ethical standards

All the participants and their legal guardians were requested to sign an informed consent. All procedures were approved by the ethical committee of the University of Trieste (protocol code 122/2022, 23.05.2022).

Declaration of Competing Interest

The authors did not receive support from any organization for the

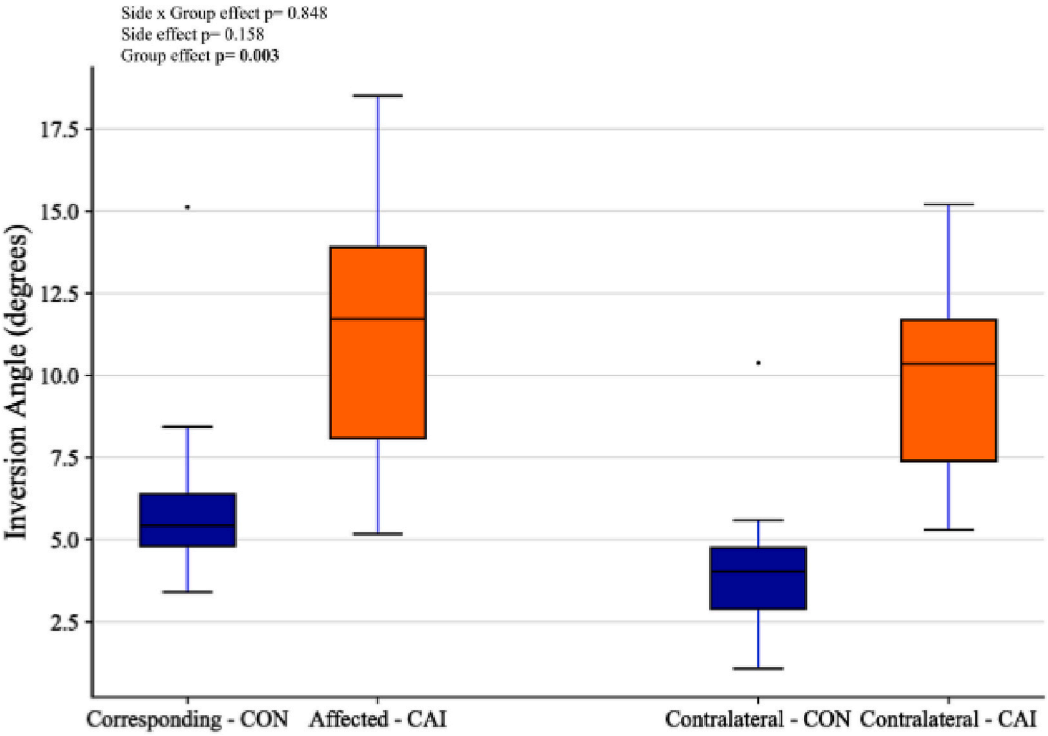

Fig. 1. Boxplots representing the difference in the inversion angle (degrees) during the monopodalic stance of the affected/corresponding and contralateral limb in healthy controls (CON) (n = 10, blue) and individuals with chronic ankle instability (CAI) (*n* = 10, orange). Significance for mixed-factors ANOVA (within group: side; between group: CON vs CAI). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

submitted work.

Data availability

Anonymized data can be requested upon reasonable request to the corresponding author.

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