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RELIABILITY OF TWO-DIMENSIONAL KINEMATIC ASSESSMENT OF SINGLE-LEG LANDING, COUNTERMOVEMENT JUMP, AND BROAD JUMP TECHNIQUES AMONG ELITE HANDBALL PLAYERS

ZANESLJIVOST DVODIMENZIONALNE KINEMATIČNE ANALIZE TEHNIČNE IZVEDBE ENONOŽNEGA PRISTANKA, SKOKA Z NASPROTNIM GIBANJEM IN SKOKA V DALJINO PRI VRHUNSKIH ROKOMETAŠIH

ABSTRACT

The aims of this study were: a) to assess the intra-session reliability of two-dimensional kinematic variables related to the knee, hip, and trunk joints, and b) to compare the results between subjectively and objectively identified key movement positions in single-leg countermovement jumps (SLCMJ), broad jumps (SLBJ), and drop landings. Eighty elite handball players (mean age 21.8 years; weight 92.0 kg; height 1.9 m) participated in the study. Three repetitions of each test, using both the dominant and non-dominant legs, were video recorded from lateral and frontal planes. Kinematic analysis was performed manually using Kinovea software. Inclinations of the shin, thigh, pelvis, and trunk (absolute variables) were calculated based on anatomical landmarks, along with joint angles (relative variables). Key movement positions were identified subjectively by expert assessment and objectively by the time point of the highest vertical ground reaction force for each task. The results indicated moderate-excellent reliability for drop landing test ($ICC_{2.1}$ = 0.54-0.99), moderate-good reliability ($ICC_{2.1}$ = 0.51-0.83) for SLCMJ, and poor-moderate reliability for SLBJ in both the push off ($ICC_{2.1}$ = 0.01-0.81) and landing phases ($ICC_{2.1}$ = 0.10-0.86). Significant differences were found between the results from subjective and objective key movement position identification ($p < 0.05$). Based on the results, we recommend conducting at least three test repetitions and averaging the outcomes to ensure reliability when performing manual 2D kinematic analysis with manual marker placement, as well as maintaining consistency in the criteria used to determine key movement positions for variable extraction.

Keywords: jump performance, stability, validity, reproducibility, consistency

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IZVLEČEK

Glavna cilja naše raziskave sta bila: a) oceniti znotrajobiskovno zanesljivost izračunanih naklonov telesnih segmentov in kotov v sklepih z dvodimenzionalno (2D) kinematično analizo in b) primerjati rezultate omenjenih spremenljivk med subjektivno in objektivno določenima ključnima gibalnima položajema pri enonožnem skoku z nasprotnim gibanjem (SLCMJ), skoku v daljino (SLBJ) in pristanku. V raziskavi je sodelovalo osemdeset vrhunskih rokometašev (povprečna starost 21,8 let; teža 92,0 kg; višina 1,9 m). Izvedli so tri ponovitve vsakega testa z dominantno in nedominantno nogo. Testi so bili posneti v bočni in čelni ravnini, kinematična analiza posnetkov pa je bila izvedena z uporabo programske opreme Kinovea. Izračunane so bile naslednje spremenljivke: nagib goleni, stegna, medenice in trupa (absolutne spremenljivke) ter koti v sklepih med segmenti (relativne spremenljivke). Ključni gibalni položaji za izračun spremenljivk so bili določeni subjektivno na podlagi ocene merilca in objektivno glede na trenutek največje sile na podlago. Rezultati so pokazali zmerno-odlično zanesljivost spremenljivk pri testu pristanka ($ICC_{2.1}$ = 0,54–0,99), zmerno-dobro zanesljivost ($ICC_{2.1}$ = 0,51–0,83) pri SLCMJ ter slabo-zmerno zanesljivost pri SLBJ, tako v fazi odriva ($ICC_{2.1}$ = 0,01–0,81) kot v fazi pristanka ($ICC_{2.1}$ = 0,10–0,86). Ugotovljene so bile razlike v rezultatih med subjektivnim in objektivnim kriterijem določitve ključnega gibalnega položaja za analizo ($p < 0.05$). Na podlagi rezultatov za zagotovitev zadovoljive zanesljivosti priporočamo analizo vsaj treh skokov in konsistentno uporabo enega kriterija pri določitvi ključnega gibalnega položaja za izračun spremenljivk.

Ključne besede: uspešnost skoka, stabilnost, veljavnost, ponovljivost, konsistentnost

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INTRODUCTION

Jumping and landing tasks are valuable diagnostic tools in sports performance and injury prevention (Bishop et al., 2022). These movements assess key aspects of athletic ability, such as neuromuscular performance in the lower limbs (kinetics), while also evaluating movement strategies (kinematics) (Kotsifaki et al., 2020). By analyzing jump and landing mechanics, coaches and sports scientists can identify movement inefficiencies or asymmetries that may increase the risk of injury, particularly in the lower extremities.

However, there is still limited knowledge about easy-to-use video assessment methods that can provide objective kinetic and kinematic data, offering greater validity than qualitative assessments. Since torque is a product of muscle force and its lever arm, which changes with joint angles, the spatial orientation and movement of body segments directly affect the magnitude of jump impulse and, consequently, the jump outcome (Cushion et al., 2022; Floría et al., 2016; Kotsifaki et al., 2020; Macedo Alfano Moura & Alves Okazaki, 2022). Furthermore, poor technical execution in jumps or landings can result in reduced force production and inefficient transfer through the kinetic chain, leading to suboptimal force distribution on soft tissues and joint structures. This increases the risk of both chronic and acute injuries (Bakker et al., 2016; De Bleecker et al., 2020; Moore, 2016; Mousavi et al., 2020; Pedley et al., 2020). Thus, jump performance depends not only on muscle strength and power but also on the technical execution of the movement (Chapman & Sanderson, 1990; Dowling & Vamos, 1993). Therefore, integrating kinematic with kinetic variables to assess an athlete's condition from both a performance and injury risk perspective should be an essential component of sports diagnostics (Floría et al., 2016; Kotsifaki et al., 2020; Saito et al., 2022).

While three-dimensional (3D) motion analysis is considered the gold standard for measuring movement kinematics—using high-frequency cameras, retroreflective markers, and specialized software (Alt Murphy et al., 2018) — its application in clinical settings is limited due to high costs and time-consuming data capture (Mousavi et al., 2020). An alternative is two-dimensional (2D) kinematic analysis, which is more affordable, easier to use, and compatible with free software. Previous studies have demonstrated that 2D kinematic analysis is a reliable and valid method compared to 3D (Della Villa et al., 2022; Ortiz et al., 2016; Ramirez et al., 2018). Moreover, the reliability of 2D kinematic variables in the sagittal and frontal planes has been confirmed for running and direction change analyses, showing good intra- and interrater reliability (Maykut et al., 2015).

Nonetheless, there is a lack of research on the reliability of 2D kinematic variables particularly in single-leg jumping and landing, which are common movement strategies in sports and a frequent focus in sports diagnostics. Understanding the technical execution during critical movement phases (i.e., key positions, KP) is crucial, as imbalances in force production and transfer through the kinetic chain can lead to inefficient movement patterns and injuries (Moore, 2016; Mousavi et al., 2020). Analysis of the force-time curve during a countermovement jump shows that the center of mass (COM) reaches its lowest point at peak ground reaction force (GRF) time point (McMahon et al., 2018). At this time point, the knee often displays a marked dynamic valgus position (Barfod et al., 2019; Hewett et al., 2005; Hewett & Myer, 2011; McLean et al., 2005), a factor associated with an elevated risk of both acute and chronic knee injuries. These include injuries to the anterior cruciate ligament (ACL) and medial collateral ligament (MCL), as well as conditions like anterior knee pain and patellofemoral pain (Bakker et al., 2016; Vosoughi et al., 2021), which are common in handball due to repeated single-leg jumping and landing tasks.

The challenge with 2D kinematic analysis lies in ensuring its reliability and validity when assessing dynamic, multi-planar body movements. Therefore, the primary aim of this study was to determine whether 2D kinematic variables related to the knee, hip, and trunk joints during single-leg countermovement jumps (SLCMJ), single-leg drop (SLD) landings, and the push off and landing phases of single-leg broad jumps (SLBJ) can be reliably assessed through manual marker identification in video recordings from the frontal and sagittal planes. Additionally, we aimed to examine the differences between the variables extracted from subjectively and objectively identified key movement positions. We hypothesized that the reliability of the kinematic variables would be excellent ($ICC_{2.1} > 0.9$), regardless of leg dominance (dominant or non-dominant), criteria used (objective or subjective key movement position identification), and the specific test performed (CMJ, SLBJ, or SLD). Furthermore, we expected no significant differences in kinematic variables between subjective and objective key position identification, thus confirming the validity of subjective criteria for determining key movement position in 2D kinematic analysis.

METHODS

Study design and participants

This was a cross-sectional study conducted in a single visit, with the total duration of approximately 45 minutes. Eighty elite team handball players from the first national Slovenian league, each with at least 10 years of training experience, were recruited. The participants were (average [SD]) 21.8 (3.9) years old, 1.90 (0.06) m tall and weighed 92.0 (9.6) kg. All players were actively engaged in regular handball training, practicing at least five times per week at their clubs over the previous five years.

Inclusion criteria required participants to be free from musculoskeletal injuries or pain syndromes within the last year, as well as any medical conditions that could be aggravated by the testing procedures. Participants were instructed to avoid strenuous activity for two days prior to testing. Before data collection, they were fully informed about the study protocol and signed an informed consent form. They wore only tight-fitting shorts (mid-thigh length), low-ankle socks, and low-ankle training shoes of their choice to minimize any influence on the testing process. Since the testing procedures were routinely performed as part of their physical preparation in regular training, no additional familiarization session was necessary. The experimental procedures were reviewed and approved by the University of Ljubljana, Faculty of Sport Ethics Committee (reference number: 14:2023) and adhered to the tenets of the Oviedo Convention and Declaration of Helsinki.

Testing procedures

Before testing, participants completed a warm-up protocol consisting of 10 minutes of light running, followed by 5 minutes of dynamic stretching and 5 minutes of dynamic strength exercises that simulated the testing drills (lunges and jumps), led by a qualified member of the research team. After the warm-up, we attached black and white markers (unfilled circles with a 25-millimeter outer diameter and a 2-millimeter inner diameter) to nineteen anatomical points, following established procedures in the literature (Puig-Diví et al., 2019). Markers were placed on the sternum, the midpoint of the thigh (measured halfway between the midpoint of the patella and the anterior superior iliac spine using a measuring tape), the center of the patella, and the center of the ankle joint in the frontal plane. An additional telescopic marker was positioned as an extension of the great trochanter, five centimeters laterally from the body. In the sagittal plane, markers were placed at the center of the deltoid muscle, on the great trochanter, lateral epicondyles, and lateral malleoli (see Figures 1 and 2). Marker placements were determined through palpation.

Participants were instructed to perform SLCMJs, SLBJs, and SLD landing tests. Each participant completed three repetitions of each test. Detailed information on how the dominant leg was determined is provided in the individual test descriptions. The sequence of tests (SLBJ, SLCMJ, and SLD landing) and the order of leg use were randomized to minimize systematic errors due to fatigue. All jumps and landings were performed on a parquet floor.

Single leg countermovement jump test

Following the procedures outlined by Šarabon et al. (2020), participants performed the jumps while standing on one leg on a bilateral force plate (model 9260AA6, Kistler, Winterthur, Switzerland). They were instructed to lower themselves as quickly as possible from a single-leg standing position into a half-squat (see Figures 1 and 2) and then jump as high as they could. A jump was deemed invalid and required repetition if the participant landed on both feet, touched the ground with any part of their body other than the jumping foot, lost balance after landing, or moved their arms away from their hips. In general, maximum four repetitions were conducted. The dominant leg was determined post hoc as the leg with which the participant achieved the higher jump. Jump height was quantified using the impulse-momentum method in MARS software (Measurement, Analysis and Reporting Software, S2P, Ljubljana, Slovenia).

Single leg drop landing test

Participants were instructed to assume a single-leg stance on a platform elevated 0.3 m above the ground. Following the procedures detailed by Saito et al. (2022), upon hearing the signal "ready," participants placed their hands on their hips, looked forward, and extended the leg they would land on. When the signal "hop" was given, participants dropped down from the platform and landed on a force plate (model 9260AA6, Kistler, Winterthur, Switzerland). They were required to achieve a balanced position and maintain it for five seconds (see Figures 1 and 2). The task was considered invalid and required repetition if the participant was unable to hold the balanced position for at least five seconds, landed on both feet, touched the ground with any part of their body other than the landing foot, lost balance after landing, or moved their arms away from their hips. In general, three to maximum five repetitions were conducted. The dominant leg was determined post hoc based on the vertical dynamic postural stability index (DPSI) at landing, which was measured using the force plates and analyzed with MARS software (Measurement, Analysis and Reporting Software, S2P, Ljubljana, Slovenia), following the equations presented by Wikstrom & Borsa (2005).

Single leg broad jump test

The test was conducted in a standardized space designated for post-hoc video analysis. A rectangle measuring 3.2 m by 1.7 m was marked on the floor using 0.05 m thick adhesive tape. Following the procedures outlined by Dobbs et al. (2015), participants began in a standing position on their take-off foot at the center of the shorter edge of the marked area. They were instructed to push off with the intent of jumping as far as possible, landing on the same leg and maintaining the position for an additional two seconds (the broad jump analysis is presented in Supplementary Material C, available at: https://osf.io/r4fxv/?view_only=130a038442344c f28e2d8e9591bcfa7a). The dominant leg was determined post hoc as the leg that achieved the greater distance. The task was deemed invalid and required repetition if the participant landed on both feet, touched the ground with any part of their body other than the jumping foot, lost balance after landing, or moved their arms away from their hips. In general, three to maximum five repetitions were conducted.

Video recording and data processing

The technical execution of the movement was recorded with two Panasonic DMC-FZ200 cameras (Panasonic Corporation, Kadoma, Osaka, Japan) at a capture frequency of 100 Hz. All push offs and landings were captured in both the frontal and sagittal planes for the dominant and non-dominant legs. The cameras were positioned at one m height, three meters sagittal or frontal relative to the participants. Video recordings were imported to and analyzed with Kinovea software (Version 0.9.5, Kinovea Open-Source Project, www.kinovea.org). The reliability and validity of the software for obtaining kinematic parameters have been previously verified (Puig-Diví et al., 2019).

Before analysis, video recordings of the SLCMJ and SLD landing tests were calibrated in 2D space using the 0.3 m high vertical edge of the wooden box as a reference object, which was placed 0.05 m behind the force plates. For the SLBJ push off phase and landing phase, video recordings were calibrated using a marked rectangle on the floor. Specifically, the longer 3.2 m edge of the rectangle was used as a horizontal reference for sagittal plane analysis, while the shorter 1.7 m edge was used for frontal plane analysis.

Time synchronization

Before conducting the 2D kinematic analyses, video recordings of the SLCMJ and SLBJ push off phases were time-synchronized with the vertical component of the GRF data in MARS software (Measurement, Analysis and Reporting Software, S2P, Ljubljana, Slovenia). The start of the unloading phase for the SLCMJ was synchronized with the video recording when the downward movement of the marker placed over the greater trochanter was visually observed.For the SLD landing and SLBJ landing phases, synchronization occurred between the point at which the vertical component of the ground reaction force signal reached 20 N and the visually observed first contact of the foot with the force plate. The initiation of the downward movement and the first foot contact were identified through visual inspection of the video, with a precision of 0.01 seconds for all assessments.

Absolute and relative kinematic variables calculation

The markers were zoomed-in to the maximum extent and precisely marked using a computer mouse. After this we extracted the coordinates of the placed markers (x, y). We exported the coordinated to Excel (Microsoft Office Excel 2019, Microsoft, Washington, USA) and calculated the kinematic variables as follows. Body segments were firstly defined as a line between two markers (x_1, y_1 and x_2, y_2; sagittal: shin, femur, trunk, and frontal: shin, femur, hip and trunk).

Then, slope (k) for each segment was calculated as the ratio of the x change to the y change. Absolute kinematic variables represented the inclination of body segment relative to vertical or horizontal planes (Minosse et al., 2022). Deviations from vertical line in degrees were calculated for each segment in both planes following the equation:

$$90° - \arctan(k) \times \frac{180}{\pi},$$

and, only for hip angle in the frontal plane the deviation of the pelvis line from the horizontal plane was calculated with the equation**:**

$$\arctan(k) \times \frac{180}{\pi}.$$

Moreover, the relative kinematic variables represented joint angles, calculated between two adjacent body segments, following the equation:

$$\arctan\left|\frac{k_2 - k_1}{1 + k_1 \times k^2}\right| \times \frac{180}{\pi}$$

Schematic illustrations of the absolute and relative kinematic variables are presented in Figures 1 and 2. Finally, the amplitudes of the countermovement during the SLCMJ and SLBJ push off phases were calculated as the change in the vertical position (y) of the greater trochanter between the single-leg standing position and the KP time points. Additionally, the amplitude of the vertical position change of the greater trochanter during SLD landing and the SLBJ landing phase was calculated between the first contact of the foot with the force plate and the KP time points. The time points were determined using synchronized video recordings and force plate data, with visual inspection of the video conducted at a precision of 0.01 seconds.

Key position determination based on subjective and objective criteria

We performed all analyses at a crucial time point of the movement, referred to as the KP, using two criteria for KP identification: objective (OBJ) and subjective (SUB). This was done separately for the SLCMJ, SLD landing, SLBJ push off and landing phase.

For the *OBJ analysis* of the SLCMJ and SLBJ push off, the KP was defined as the moment at the end of the eccentric phase of the jump. This is based on the understanding that the COM reaches its lowest vertical position when the GRF is at its peak (McMahon et al., 2018). This moment is also associated with the most pronounced dynamic knee valgus position (Barfod et al., 2019; Hewett et al., 2005; Hewett & Myer, 2011; McLean et al., 2005), which has been linked to an increased risk of both acute and chronic knee injuries, such as anterior cruciate ligament (ACL) and medial collateral ligament (MCL) injuries, as well as anterior knee and patellofemoral pain (Bakker et al., 2016; Vosoughi et al., 2021). Similarly, during single-leg landings, the dynamic knee valgus position is most prominent at the peak GRF time point (Heebner et al., 2017; Saito et al., 2022). Therefore, for the OBJ analysis of the landing and SLBJ landing tests, the KP was determined at the time of peak vertical GRF during the SLD landing test. The "Stopwatch" module in Kinovea software was utilized to track the time from the initiation of the movement (time normalized with force plates) to the KP.

For the *SUB criteria*, the KP for all tests was consistently defined as the moment when the greater trochanter reached its lowest vertical position, determined through expert visual inspection of the video, at a precision of 0.01 seconds for all analyses.

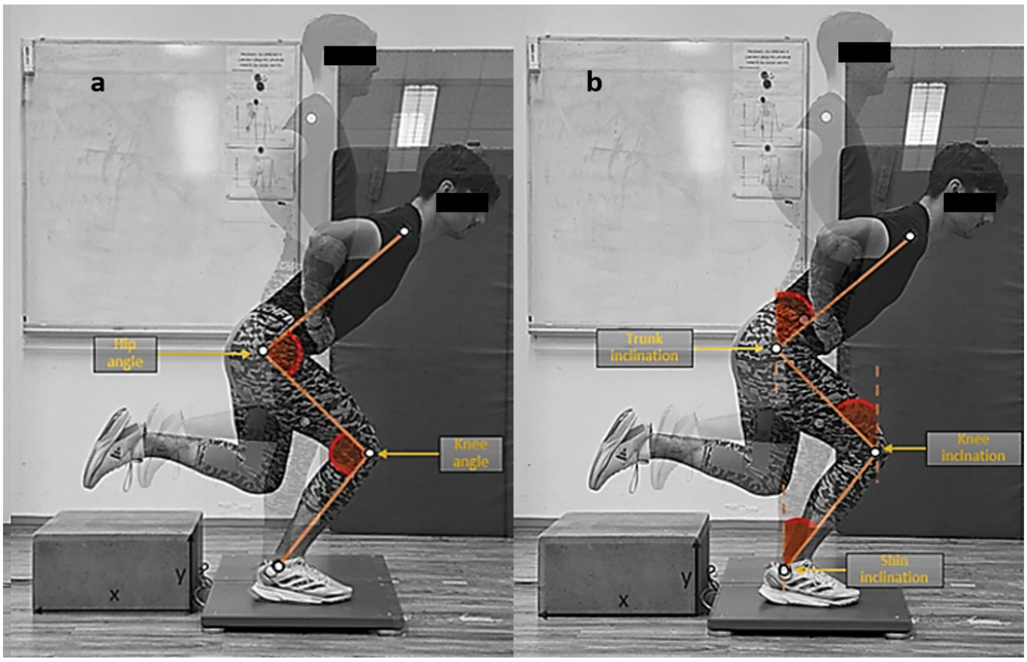


Figure 1. Presentation of (a) relative and (b) absolute kinematic variables in the sagittal plane.

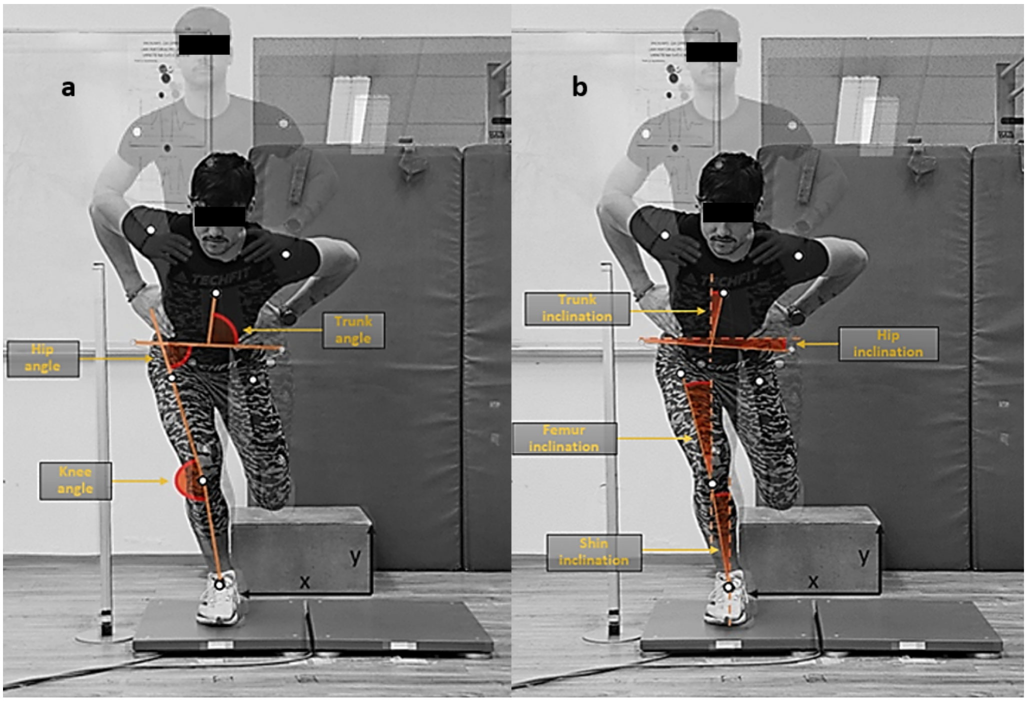


Figure 2. Presentation of (a) relative and (b) absolute kinematic variables in the frontal plane.

Statistical analyses

The obtained kinematic variables were reported as averages and standard deviations (SD). Before analysis, the normality of the data distributions for all variables was verified using the Shapiro-Wilk test (all $p \geq 0.195$). Intra-session reliability across the three repetitions was calculated using the intraclass correlation coefficient ($ICC_{2.1}$) with 95% confidence intervals (CI) — which served as a main statistical outcome variable in our study. According to the latest guidelines, $ICC_{2.1}$ values were interpreted as follows: values < 0.50 indicate poor reliability, $0.50 \leq ICC_{2.1} < 0.75$ indicate moderate reliability, $0.75 \leq ICC_{2.1} < 0.90$ indicate good reliability, and $ICC_{2.1} > 0.90$ indicate excellent reliability (Koo & Li, 2016).

Absolute reliability was assessed using the coefficient of variance (CV), with values ≤ 10% considered acceptable (Cormack et al., 2008). Additionally, the standard error of measurement (SEM) was calculated using the formula $SEM = SD \cdot \sqrt{(1 - ICC_{2.1})}$, where SD refers to the pooled standard deviation of the three repetitions (Dvir, 2015). The statistical significance of differences between the three repetitions was analyzed using a repeated measures one-way analysis of variance (ANOVA).

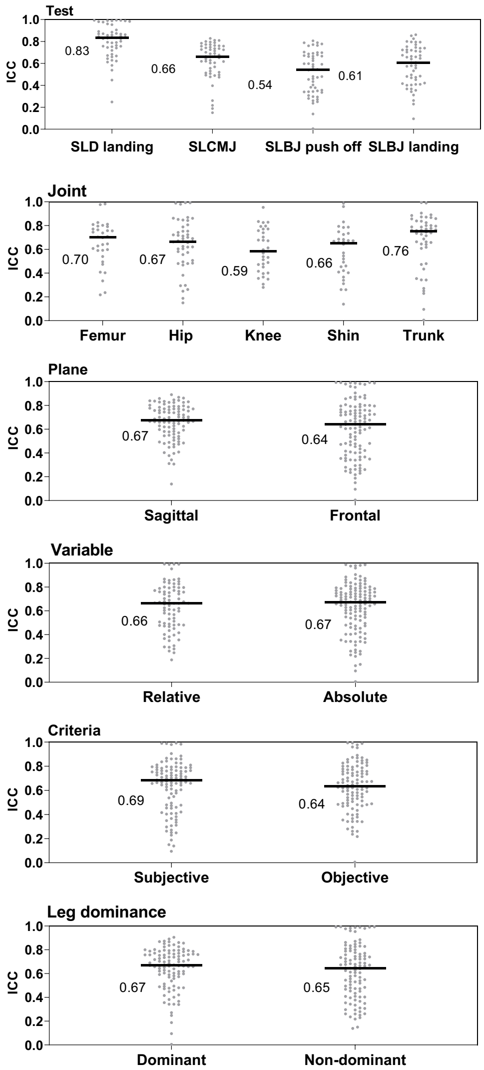
The differences between the results of SUB and OBJ KP identification were compared with paired samples t-test. To determine the effect size of the test statistic, we used Cohen's coefficient d according to the author's criteria (Cohen, 1988.). A value of 0.2 indicates a weak; 0.5 medium; and 0.8 or higher a strong connection. Pearsons's correlation coefficient (r) was additionally calculated between the results of both criteria. The interpretation of the results was as follows: using the following criteria: 0.0 indicates no correlation; 0.1–0.29 small; 0.3–0.49 medium; 0.5–0.69 large; 0.7–0.89 very large, and 0.9–1 perfect correlation (Akoglu, 2018).

Statistical analyses were performed in the RStudio: Integrated Development Environment for R (v4.3.3.; Posit team [2024], Boston, MA; http://www.posit.co/, accessed in April 2024), while figures were generated using the GraphPad Prism (v8, GraphPad, San Diego, California, United States). The cut-off for statistical significance was set at $p < 0.05$.

RESULTS

Figure 3 illustrates the $ICC_{2.1}$ results for kinematic variables, presented separately by variable conditions. $ICC_{2.1}$ values ranged from 0.01, observed in the "SLBJ push off with dominant leg trunk inclination variable at OBJ identification of KP for analysis in the frontal plane" to 1.00 in "SLD landing with non-dominant leg hip inclination variable at OBJ identification of KP for analysis in the frontal plane."

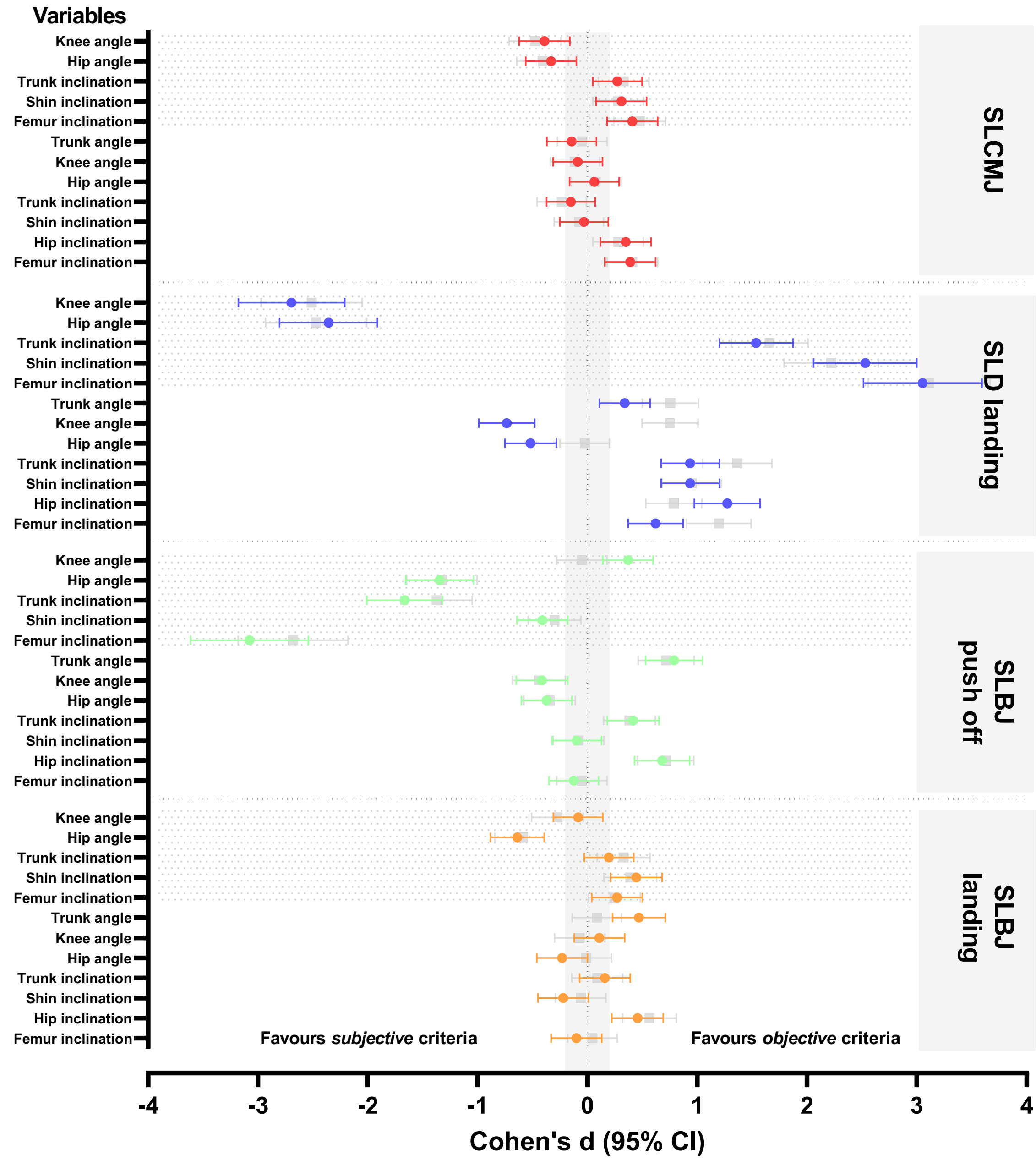
CV values ranged from 1.1% to 84.0% in "SLD landing with dominant leg knee angle variable at OBJ identification of KP for analysis in the frontal plane" and "SLBJ push off with non-dominant leg shin inclination variable at OBJ identification of KP for analysis in the frontal plane," respectfully. SEM values ranged from 1.45° to 12.14° in "SLD landing with dominant leg shin inclination variable at OBJ identification of KP for analysis in the frontal plane" and " SLBJ push off with non-dominant leg trunk angle variable at OBJ identification of KP for analysis in the frontal plane," respectfully. Notably, ANOVA revealed statistically significant differences between the three repetitions in 39 out of 192 variables (Supplementary Material A, available at: https://osf.io/r4fxv/?view_only=130a038442344cf28e2d8e9591bcfa7a).



Notes: ICC – Intraclass Correlation Coefficient type 2.1; SLD – single-leg drop; SLCMJ – single-leg countermovement jump; SLBJ – single-leg broad jump. Values represent the median ICC across all variables. Each dot represents the ICC result for a specific variable. All of the tables can be found in Supplementary material A (https://osf.io/r4fxv/?view_only=7e98cc72d56b49ed976a841c350349b0)

Figure 3. Summary of intraclass correlation coefficient results for kinematic variables, presented separately by variable conditions.

Figure 4 illustrates Cohen's d results for differences between kinematic variables calculated based on OBJ and SUB KP identification criteria for SLCMJ, SLD landing, SLBJ push off, and landing phase. T-test results revealed statistically significant difference between the criteria in 70 out of 96 variables. The magnitudes of difference ranged from -3.08 to 3.19 for "SLBJ push off with dominant leg femur inclination variable in the frontal plane" and "SLD landing with non-dominant leg femur inclination variable in the saggital plane", respectively. The results were statistically significantly correlated in 96% of the cases (92/96 variables). The correlation coefficient ranged from -0.34 observed in "SLD landing with non-dominant leg knee angle variable in the frontal plane" to 0.99 in "SLBJ landing with dominant leg hip inclination variable in the frontal plane" (Supplementary Material B, available at: https://osf.io/r4fxv/?view_only=130a038442344cf28e2d8e9591bcfa7a).



Notes: SLD – single-leg drop; SLCMJ – single-leg countermovement jump; SLBJ – single-leg broad jump. Cohen's d effect sizes are presented with 95% confidence intervals (CIs) for the dominant leg (filled circles) and the non-dominant leg (transparent gray squares behind the circles). The shaded area over the first five variables of each test represents sagittal plane variables, while the unshaded area represents frontal plane variables. Variables labeled "angle" indicate relative measurements, and those labeled "inclination" represent absolute measurements. Negative values indicate that higher variable values were found when calculated based on subjective key position identification criteria. Full results, including means, standard deviations, paired-samples t-test statistics, mean differences, Pearson correlations, typical errors, and Cohen's d statistics, can be found in Supplementary Materials A and B at https://osf.io/r4fxv/?view_only=130a038442344cf28e2d8e9591bcfa7a.

Figure 4. Summary of Cohen's d results for differences in kinematic variables calculated based on objective and subjective key position identification criteria.

DISCUSSION

2D kinematic analysis is a commonly used method in sports practice for evaluating the technical execution of movement. However, there is limited research confirming the reliability of this method when applied to SLCMJs, SLBJs, and SLD landing tasks. Therefore, the aim of our study was to assess the reliability of variables obtained through a simplified method of 2D kinematic analysis in the frontal and sagittal planes during these sport-specific movements. Additionally, we aimed to compare results between subjectively and objectively identified KPs for analysis. The findings did not support our first hypothesis, which assumed excellent reliability across all obtained variables. The highest reliability of kinematic variables, as measured by the $ICC_{2.1}$, was found for the SLD landing test, regardless of leg dominance, KP identification criteria, or plane of analysis (sagittal or frontal). In contrast, the SLBJ test exhibited poor to moderate reliability for both the push off and landing phases. Furthermore, we found that the results for kinematic variables differed when calculated at the time point identified subjectively as the peak GRF condition compared to the actual peak GRF. Consequently, our second hypothesis—supporting the validity of SUB criteria for determining KP in 2D kinematic analysis—must be rejected. Possible reasons for the results are emphasized in the future text.

The reliability results for the SLD landing test from our study are presented in Supplementary Material A, Tables 2 and 3, available at https://osf.io/r4fxv/?view _only=130a038442344cf28e2d8e9591bcfa7a. Good to excellent reliability was reported across all kinematic variables ($ICC_{2.1} > 0.75$), with CV indicating acceptable reliability throughout ($CV < 10\%$). Good-excellent reliability of the kinematic variables can be attributed to several factors. The sample consisted of professional handball players who, through extensive training, had likely become familiar with and mastered the technical execution of single-leg landings. Additionally, the test is easier to perform from a coordination standpoint compared to other tests in this study, as it only requires force absorption during landing rather than body propulsion, ultimately contributing to the better reliability of the obtained variables. Previous research has reported similar findings, specifically demonstrating good to excellent reliability for the knee valgus variable (Munro et al., 2017; Peebles et al., 2021). To the authors's knowledge this was the first study examining movement technique in SLD landing. Studies using bilateral landings show comparable results, with trunk inclination in the frontal plane achieving excellent reliability for both the dominant ($ICC_{2.1} = 0.98$) and the non-dominant legs

($ICC_{2.1}$ = 0.99) (Dingenen et al., 2014). Literature indicates that knee and hip flexion in the sagittal plane are typically evaluated at maximum knee flexion (Belyea et al., 2015; Robles-Palazón et al., 2021). Previous studies have reported good to excellent reliability for knee angle ($ICC_{2.1}$ = 0.73–0.92) and for hip angle ($ICC_{2.1}$ = 0.80–0.97) during the landing phase of a bilateral drop jump for the dominant leg (Belyea et al., 2015; Robles-Palazón et al., 2021). However, our study found moderate to good reliability for knee and hip flexion in the sagittal plane for the dominant leg. We believe that this discrepancy may be attributed to the unilateral instead of bilateral landings; while bilateral landing likely provides greater stability, which can reduce variability in performance and lower dependence on lower extremity strength. In addition, comparisons between subjectively and objectively derived kinematic variables showed statistically significant differences and moderate to strong correlations for all variables, except one (*SLD landing test: hip angle with non-dominant leg in the frontal plane*), in both the frontal and sagittal planes (Supplementary Material B, Table 2 available at: https://osf.io/r4fxv/?view_only=130a038442344cf28e2d8e9591bcfa7a). These findings suggest that the SUB assessment of the KP in the SLD landing test may not be accurate, possibly because the peak GRF occurs before the lowest point of the COM. This misalignment may be related to the activation of inhibitory neural mechanisms in the leg muscles during landing, where high forces trigger a reduction in force generation (Aagaard et al., 2000). This effect might be particularly pronounced in single-leg actions, where impact forces per leg are high.

The reliability results of SLCMJ kinematic variables are presented in Supplementary Material A, Table 4 and 5, available at: https://osf.io/r4fxv/?view_only=130a03844234 4cf28e2d8e9591bcfa7a. Our study demonstrates moderate reliability ($ICC_{2.1}$ = 0.50–0.75) for kinematic variables in the SLCMJ, irrespective of the criteria, leg, or plane of motion. Additionally, the kinematic variables exhibited acceptable CV values (CV < 10%), indicating consistent measurement precision. To the author's knowledge, only one study (Miller & Callister, 2009) has examined the reliability of 2D kinematic variables in SLCMJ, finding moderate reliability for knee valgus using both relative (tibia-femur angle) and absolute (femur inclination from vertical axis) kinematic measures. Their findings align with ours, while we also found moderate reliability for knee valgus (knee angle and femur inclination) for the dominant leg. There is a lack of studies investigating the reliability of other variables obtained using the 2D kinematic analysis method. Focusing solely on variables in the frontal plane and at a specific joint (e.g., knee valgus) underestimates the intersegmental coordination required for complex, multi-segmental movements like jumping (Kiefer et al., 2013; Nagelli et al., 2018). Knee valgus is not only a result of poor knee control but can also be a consequence of poor control and function of interdependent segments (trunk-hip-knee-ankle). Therefore, for causal relationships in injury analysis and physical performance, it is necessary to consider variables in both the frontal and sagittal planes and across multiple segments. Thus, our simplified 2D kinematic analysis method represents a stepping stone for further research in the field of 2D kinematic analysis. Furthermore, statistically significant differences were found between subjectively and objectively derived kinematic variables (Supplementary material B: Table 3 available at: https://osf.io/r4fxv/?view_only=130a038442344cf28e2d8e9591bcfa7a) for all variables in the sagittal plane and in 5 out of 14 variables in the frontal plane. This discrepancy in the results may be attributed to the movement patterns employed by the subjects. It is not necessarily the case that the peak GRF occurs at the lowest point of the movement amplitude. This discrepancy could be attributed to insufficient strength or an excessively deep descent, where the energy generated during the eccentric phase is not efficiently transferred to the concentric phase of the movement (Kennedy & Drake, 2018).

In the analysis of the SLBJ, the push off and landing phases were examined separately. The push off phase is presented in Supplementary material A: Tables 6 and 7 (available at: https://osf.io/r4fxv/?view_only=130a038442344cf28e2d8e9591bcfa7a), where poor to good reliability was observed for the kinematic variables, irrespective of the criteria, leg dominance or plane of analysis ($ICC_{2.1}$ = 0.05–0.81). Similar results were found for SLBJ landing, presented in Supplementary material A: Table 8 and 9 (available at: https://osf.io/r4fxv/?view_only=130a038442344cf28e2d8e9591bcfa7a). We report poor to good reliability for SLBJ landing kinematic variables, irrespective of the criteria, leg dominance or plane of analysis ($ICC_{2.1}$ = 0.09–0.86). Notably, the coefficient of variation indicated that acceptable reliability was achieved across all relative kinematic variables (i.e., angle variables) during the SLBJ push off and landing phases (CV < 10%). In contrast, the absolute kinematic variables (i.e., inclination variables) during the SLBJ push off and landing phases mostly demonstrated higher CV values, indicating unacceptable reliability (CV = 3.7%–84.0%). The literature lacks studies evaluating the reliability of 2D kinematic variables in the SLBJ, particularly given the increased complexity of the task, which is associated with greater variability in movement execution, especially in individuals not trained in the technical aspects of the task. The SLBJ requires the individual to shift their center of gravity forward through eccentric-concentric contractions and to jump as far as possible, resulting in the expression of both horizontal and vertical GRF vectors. Furthermore, it could be that the subjects in our sample were not accustomed to such movements in their training regime. Given the complexity of the movement and the reliability results obtained in our kinematic variables, it can be concluded that for more complex movements such as the SLBJ, averaging more than three test repetitions is necessary, along with the implementation of an appropriate learning phase for jump technique. In the case of SLBJ push off and landing, mostly all of the kinematic variables showed statistically significant differences and moderate to strong correlations (Supplementary material B: Table 4 and 5 available at: https://osf.io/r4fxv/?view_only=130a03844 2344cf28e2d8e9591bcfa7a). The results could be due to the time-synchronization, which was applied to SLBJ push off and landing with SLCMJ and SLD landing GRF signal data, respectfully. These results suggest that the discrepancies in reliability may stem from the challenges associated with accurately aligning kinematic data with force plate signals, leading to inconsistencies in the measurement of SLBJ kinematic variables.

Strengths and limitations

One of the strengths of this study is its comprehensive analysis, which evaluated multiple joint angles and inclinations in both the sagittal and frontal planes through the SLCMJ, SLBJ push off and landing phases, as well as the SLD landing test. Additionally, the KP were determined using both SUB and OBJ criteria. Taken together, these approaches enabled a thorough assessment of the kinematic variables using this simplified 2D kinematic analysis method. Additionally, the study included a relatively high sample size of participants, which enhances the reliability and generalizability of the findings. Furthermore, the inclusion of elite handball players as participants ensures that the results are highly relevant to performance analysis and training optimization in high-level athletes. This focus on an elite population provides valuable insights into the movement patterns of players at the top of their sport.

Nonetheless, this study has certain limitations. Errors in identifying the KP can occur with both the OBJ and SUB criteria. In our analysis, we determined the KP based on the duration of the eccentric phase of the countermovement. It is possible that using the duration of the concentric phase instead could have yielded different results. Additionally, the duration of the landing and the countermovement in the SLCMJ and SLD landing test, respectively, was used to objectively determine the KP for analyzing the SLBJ push off and landing phases. This may have resulted in lower reliability compared to the other tests in the study. Finally, manually marking the markers in Kinovea was time-consuming and might be less accurate than using marker “tracing”. These limitations suggest that the results should be interpreted with caution, as variations in methodology could influence the findings. Further research is needed to explore alternative methods for determining the KP and their impact on the reliability of the analysis.

CONCLUSION

Based on our findings, we recommend analyzing at least three test repetitions and averaging the results to obtain reliable outcomes when performing 2D kinematic analysis with manual marker placement for single-leg jumping and landing techniques. Additionally, it is important to note that statistically significant differences exist between the SUB and OBJ identification of key movement positions during the analysis. This underscores the need for consistency in the criteria used to determine key movement positions for variable extraction. Sports practitioners should be aware of these limitations and apply additional caution and critical judgment when reading, analyzing, and interpreting the data in the future.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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