

Reliability of manual marker placement in two-dimensional kinematic analysis of single-leg landing, countermovement jump, and broad jump movement techniques

Ažbe Ribič^a, Darjan Spudič^a, Nejc Šarabon^{b,c,d,e} and Primož Pori^a

^a Faculty of Sport, University of Ljubljana, Ljubljana, Slovenia

^b Faculty of Health Sciences, University of Primorska, Izola, Slovenia

^c Andrej Marušič Institute, University of Primorska, Koper, Slovenia

^d Laboratory for Motor Control and Motor Behavior, S2P, Science to Practice, Ltd, Ljubljana, Slovenia

^e Ludwig Boltzmann Institute for Rehabilitation Research, Vienna, Austria

Purpose: Manual two-dimensional (2D) kinematic analysis is widely used in research settings to evaluate jump techniques. However, a gap remains in the literature regarding the reliability and validity of analyzing single-leg jumps. This study examines a previously overlooked source of variability in manual 2D kinematic analysis, specifically: (a) the impact of manual marker placement on anatomical landmarks and (b) the precision of visually identifying key movement time points in single-leg countermovement jumps, single-leg broad jump push-off and landing phases, and single-leg drop landings.

Methods: Eighty professional handball players (age: 21.8±3.9 years; mass: 92.0±9.6 kg; stature: 1.90±.06 m) were video recorded from lateral and frontal planes, and the analysis was manually performed using Kinovea software. The study examined 2D kinematic variables, including the inclinations of the shin, thigh, and trunk segments relative to a vertical reference line, as well as the joint angles between these segments during single-leg jumps. Reliability was assessed by comparing (a) three repetitions of manual marker placement (MP) on anatomical landmarks and (b) three repetitions of visual identification of key movement positions (KPs) during single-leg countermovement jumps, broad jump push-offs and landings, and drop landings. KPs were defined by two criteria, based on either the lowest vertical position of the greater trochanter (subjective) or peak vertical ground reaction force data (objective).

Results: The main findings of our study indicate that the reliability of marker placement and key position determination, regardless of the test, plane of motion, leg, and criteria of key position determination is acceptable (ICC= .883–.999; CV<10 %).

Conclusions: These findings confirm that manual 2D kinematic analysis reliably evaluates movement techniques during jumps and landings across different KP definitions and variable conditions.

Keywords: Jump performance, stability, validity, reproducibility, power.

Introduction

Jumps are among the most frequently employed testing methods in sports science due to their time efficiency, relative simplicity, and ability to kinematically mimic movements that occur in sports¹. Existing literature predominantly assesses jump performance through kinetic variables. However, there is a notable lack of research evaluating jump performance based on the technical execution of the jump itself. Optimal athletic performance requires precise motor control among body segments, and even minor deviations in the kinetic chain can disrupt force transmission, leading to diminished performance and increased injury risk. While, athletic performance is commonly evaluated through jump performance, it is imperative to monitor kinematic variables alongside kinetic ones, as muscle force production inherently depends on the precise positioning of body segments. Therefore, integrating kinematic with kinetic variables is essential in sports diagnostics for both performance assessment and injury prevention.²⁻⁴

The most widely used methods for objectively assessing

movement technique are kinematic analyses in three-dimensional (3D) and two-dimensional (2D) space. The gold standard for motion analysis is a high-speed 3D motion capture and marker tracking system,⁵ but its practical use is limited due to high costs and the time-intensive data collection process.^{6,7} An alternative is 2D kinematic analysis with manual marker placement (MP) on anatomical landmarks, which is more affordable, easier to analyze, and compatible with freely available software online. To ensure reliable results with video technology, it is essential to have high-quality footage, good lighting of the subject, and proper camera positioning, maintaining a consistent distance throughout.⁷ This method involves capturing and analysing movement at specific time points of interest that correspond to key positions (KPs) within the movement task, such as initial ground contact, peak force moments, the transition from braking to acceleration, and maximal joint angles.⁸⁻¹⁰ Therefore, accurately identifying KPs during jumps and landings is crucial. The literature often suggests selecting the KP where deviations from optimal motor task execution are most likely to occur. In a countermovement jump, this is typically the moment of

maximum force application to the ground, where dynamic knee valgus is most pronounced.⁸ However, current research is insufficient to conclusively determine whether variables obtained through 2D kinematic analysis at this position are reliable for practical application. Additionally, studies confirming the reliability of such analysis in other commonly used tests, like the broad jump and landing assessments, are also lacking. Joint angles are useful for analysing specific joint kinematics by focusing on relative movement between connected segments, while segment inclinations help in understanding posture, overall body orientation, and dynamic movements in relation to external references, such as the ground. However, comparisons of the reliability of these variable conditions across jumping and landing tasks remain sparse in the literature, and questions remain regarding which parameters should be used in practice.¹⁰ The use of 2D kinematic analysis has been extensively discussed in the literature, particularly regarding its reliability and validity in analysing dynamic and complex movements that occur across multiple planes, such as dynamic knee valgus.¹¹ The reliability of 2D kinematic analysis is often affected by data variability, which can stem from rater-dependent factors like inconsistencies in identifying KP and manual MP, as well as variations in the execution of movement tasks. A review of the literature revealed a lack of research specifically addressing the reliability of these critical components in kinematic analysis. The purpose of this study was to assess the intra-session reliability of 2D kinematic variables related to shin, thigh, and trunk segment inclinations relative to a vertical line and joint angles between segments. This was achieved by (a) calculating these variables from three separate independent repetitions of manual MP on anatomical landmarks, and (b) calculating them from three separate independent identifications of KPs during single-leg countermovement jumps (SLCMJ), single-leg broad jumps (SLBJ), and single-leg drop (SLD) landings. We hypothesized that the reliability of kinematic variables for MP and KP identification would be excellent ($ICC > .9$), regardless of the specific test (SLCMJ, SLBJ, or SLD landing) or variable conditions. This would confirm the validity of the results obtained using manual MP in 2D kinematic analysis of jumping and landing tasks.

Methods

Participants

The study included 80 professional male team handball players from Slovenia's first national league with 12 ± 4 years of handball training experience. The participants were 21.8 ± 3.9 years old, stature 1.90 ± 0.06 m and body weight 92.0 ± 9.6 kg with a body mass index of 25.2 ± 2.16 kg/m². All players were actively engaged in regular handball training, practicing at least five times per week at their clubs over the previous five years. The exclusion criteria required that participants had no acute musculoskeletal injuries or overload syndromes in the past year and no medical conditions that could be aggravated by the testing procedures. Individuals with a history of low back pain and knee injuries – such as ligament tears, meniscus damage, or cartilage deterioration – were excluded due to potential impacts on knee stability and function. They were required to wear tight-fitting shorts (mid-thigh length), low-ankle socks, and training shoes of their choice to ensure that clothing did not affect the tests. Since the participants were already accustomed to the testing procedures, which were part of their regular physical preparation routine, no familiarization session was deemed necessary. Prior to testing, they completed a warm-up consisting

of 10 min of light running, 5 min of dynamic stretching, and 5 min of dynamic strength exercises that simulated the testing tasks (lunges and jumps).

Experimental Design

This cross-sectional study was conducted in a single session lasting approximately 45 min. Prior to the start of the measurements, participants were fully briefed on the protocol details and provided written informed consent. The study protocol adhered to the latest revision of the Declaration of Helsinki.

After performing a standardized warm-up protocol led by a qualified member of the research team, we attached black and white markers (unfilled circles with a 25 mm outer diameter and a 2 mm inner diameter) to nineteen anatomical points, following the procedures outlined in the literature.¹² Markers were placed on the sternum, the midpoint of the thigh (halfway between the patella and the anterior superior iliac spine, measured using a tape), the center of the patella, and the center of the ankle joint in the frontal plane. Additionally, a telescopic marker was positioned as an extension of the greater trochanter, 5 cm lateral to the body. In the sagittal plane, markers were placed at the center of the deltoid muscle, on the greater trochanter, the lateral epicondyles, and the lateral malleoli (see Figure 1 and 2). Marker placements were determined through palpation. Participants were then instructed to perform SLCMJ, SLBJ, and SLD landing. Each participant completed an introductory repetition, followed by a test repetition, which was used for video analysis. Detailed information on how the dominant leg was determined is provided in the individual test descriptions. To minimize systematic errors due to fatigue, the order of the tests and the sequence of leg usage (left, right) was randomized.

Single leg countermovement jump test

Following the procedures detailed by Šarabon et al.,¹³ 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 (Figure 1 and 2), then jump as high as possible. A jump was deemed invalid and had to be repeated if the participant landed on both feet, touched the ground with any part of the body other than the jumping foot, lost balance after landing, or moved their arms away from their hips. In general, test was not repeated more than twice for each leg. 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 (Analysis and Reporting Software, S2P, Ljubljana, Slovenia).

Single leg drop landing test

Participants were instructed to assume a single-leg stance on a .3 m high platform. Following the detailed procedures outlined by Saito et al.,⁴ 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, landing on a force plate (model 9260AA6, Kistler, Winterthur, Switzerland). They were instructed to achieve a balanced position and maintain it for five seconds (Figure 1 and 2). The task was considered invalid and had to be repeated if the participant was unable to hold the balanced position for at least five seconds, landed on both feet, touched the ground with any body part other than the landing foot, lost balance after landing, or moved their arms away from their hips. In general, test was not repeated more than twice for each leg. The dominant leg was determined post-hoc, based on

the vertical dynamic postural stability index (DPSI) at landing, measured using force plates and analyzed with MARS software, following the equations presented in Wikstrom and Borsa.¹⁴

Single leg broad jump test

The test was conducted in a standardized space for post-hoc video analysis. A rectangle measuring 3.2 m x 1.7 m was marked on the floor using .05 m thick adhesive tape. Following the procedures outlined by Dobbs et al.,¹⁵ participants assumed a standing position on the take-off foot at the center of the shorter edge of the marked area. They were instructed to push off with the intention of jumping as far as possible, landing on the same leg and holding the position for an additional two seconds (SLBJ analysis is presented in the Supplementary material C, available at: https://osf.io/rzv8f/?view_only=fd0ea6ecf8a748e2a6f98d13d2f2c4f3). 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 the body other than the jumping foot, lost balance after landing, or moved their arms away from their hips. The test was performed on a parquet floor and was not repeated more than twice for each leg.

Video recording and data processing

The technical execution of the movements was recorded using two Panasonic DMC-FZ200 cameras (Panasonic Corporation, Kadoma, Osaka, Japan) at a 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 perpendicular to the plane of motion at one m height, three m sagittally or frontally relative to the participants. Video recordings were imported and analyzed with Kinovea software (Version .9.5, Kinovea Open-Source Project, www.kinovea.org). The reliability and validity of this software for obtaining kinematic parameters have been previously established.¹²

Prior to analysis, all video recordings for the SLCMJ and SLD landing tests were spatially oriented in 2D space to establish a two-dimensional coordinate system, using the rectangular side of a wooden box as an orientation object (Figures 2 and 3). The box was placed 0.05 m behind the force plates. For sagittal plane kinematic analysis, spatial calibration was additionally performed to enable quantification of the vertical displacement of the greater trochanter (amplitude variable) during the countermovement phase. This was achieved using the .3 m high vertical edge of the box (Figure 2).

For the SLBJ push-off and landing phases, video recordings were spatially oriented using a marked rectangle on the floor. To determine the amplitude during the push-off phase in the sagittal plane, spatial calibration was additionally carried out using the 3.2 m long edge of the rectangle.

Key position determination based on subjective and objective criteria

We performed knee angles and segment inclinations analyses using two criteria for KP determination: objective (OBJ) and subjective (SUB). This was done separately for the SLCMJ, SLD landing, SLBJ push off and SLBJ landing tests.

For the OBJ analysis of the SLCMJ and SLBJ push off, the KP was defined as the time point at the end of the eccentric phase of the jump. We choose this criterion based on the understanding that the center of mass reaches its lowest vertical position when the ground reaction force (GRF) is at its peak.¹⁶ This time point is also associated with the most pronounced dynamic knee valgus position,^{9,10,17,18} 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.^{19,20}

Similarly, during SLD landing, the dynamic knee valgus position is most prominent at the peak GRF time point.^{4,21} Therefore, for the OBJ analysis of the SLD landing and SLBJ landing tests, the KP was determined as a time of peak vertical GRF during the SLD landing test.

Before conducting the OBJ 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. The start of the unloading phase from GRF signal for the SLCMJ was synchronized with the video recording at the time point when downward movement of the marker placed over the greater trochanter was visually observed. For the SLD landing and SLBJ landing phases, synchronization was done between the time point at which the vertical component of the GRF signal reached 20 N and the visually observed first contact of the foot with the force plate. 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. The initiation of the movement, i.e., downward movement of the greater trochanter for SLCMJ and the first foot contact with the force plate for SLD landing, respectfully, were identified through visual inspection of the video, with a precision of .01 seconds.

For the SUB criteria, the KP for all tests was consistently defined as the time point when the greater trochanter reached its lowest vertical position, determined through expert visual inspection of the video, at a precision of .01 seconds for all analyses.

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 obtained the coordinates of the placed markers (x, y). We exported the values of the kinematic variables 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 (x1, y1 and x2, y2; sagittal: shin, femur, trunk, and frontal: shin, femur, hip and trunk).

Then, slope (k) or inclination relative to the vertical line for each body segment²² was calculated as the ratio of the x change to the y change. Absolute kinematic variables, which represented inclinations relative to vertical line in degrees were then calculated for each segment in both planes following the equation:

$$90^\circ - \arctan(k) \times \frac{180}{\pi} \quad (1)$$

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

$$\arctan(k) \times \frac{180}{\pi} \quad (2)$$

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

$$\arctan \left| \frac{k_2 - k_1}{1 + k_1 \times k_2} \right| \times \frac{180}{\pi} \quad (3)$$

Schematic illustrations of the absolute and relative kinematic variables are presented in Figure 1 and 2. Finally, the amplitude of the countermovement during the SLCMJ and SLBJ push off phases was calculated as the change in the vertical position (y) of the greater trochanter between the single-leg standing position and the KP time points (Figure 2). Additionally, the amplitude of the vertical position change of the greater trochanter during SLD landing test 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 .01 seconds

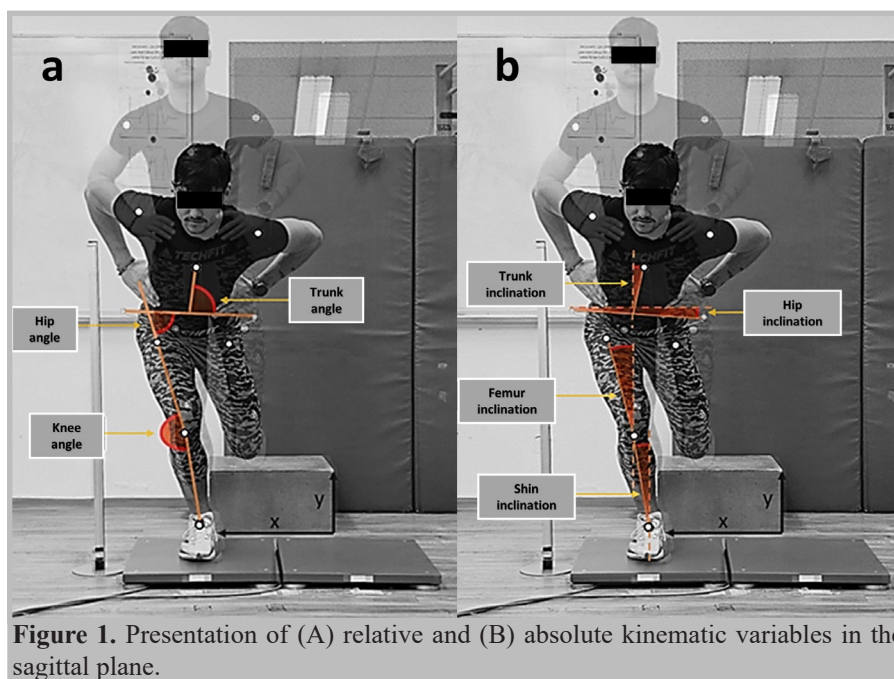


Figure 1. Presentation of (A) relative and (B) absolute kinematic variables in the sagittal plane.

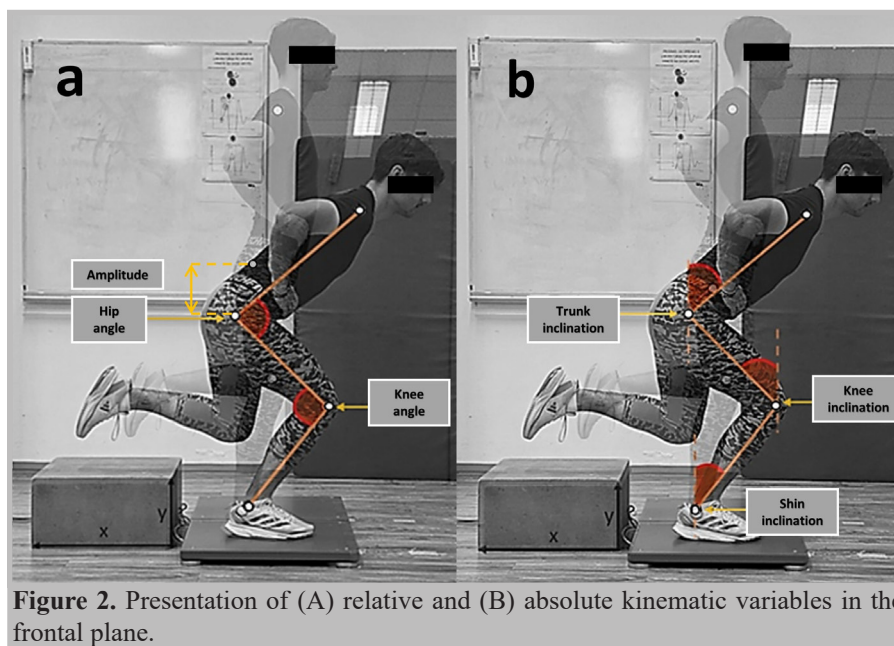


Figure 2. Presentation of (A) relative and (B) absolute kinematic variables in the frontal plane.

Definition of marker placement and key position identification reliability

The reliability of kinematic variables resulting from MP was assessed through three separate repetitions of manual MP on anatomical landmarks at the determined KP. This procedure involved erasing all marker positions between each repetition. The reliability of kinematic variables related to KP identification was evaluated by repeating the manual MP at the KP three times, from the start of the task to the KP time point. Similarly, all marker positions were erased between each repetition

Statistical analysis

The obtained kinematic variables were reported as averages \pm standard deviations (SD). Before analysis, the normality of the data distributions for all variables was verified using the Shapiro-Wilk test (all $P \geq .195$). 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 $< .50$ indicate poor reliability, $.50 \leq ICC_{2,1} < .75$ indicate moderate reliability, $.75 \leq ICC_{2,1} < .90$ indicate good reliability, and $ICC_{2,1} > .90$ indicate excellent reliability.²³

Absolute reliability was assessed using the coefficient of variance (CV), with values $\leq 10\%$ considered acceptable.²⁴ Additionally, the standard error of measurement (SEM) was calculated using the formula $SEM = SD \cdot \sqrt{1 - ICC}$, where SD refers to the pooled standard deviation of the three repetitions.²⁵ The statistical significance of differences between the three repetitions was analyzed using a repeated measures one-way analysis of variance.

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 $P < .05$.

Results

Reliability results of each particular kinematic variable for MP and KP identification for each particular test (SLCMJ, SLD landing, SLBJ push off, and SLBJ landing) — separately for plane (frontal, sagittal), criteria (SUB, OBJ criterion for KP identification), leg dominance (dominant or non-dominant) and variable type (relative – joint angles, absolute – segment inclination) are presented in Supplementary materials A (MP reliability) and Supplementary materials B (KP identification reliability) available at: https://osf.io/rzv8f/?view_only=fd0ea6ecf8a748e2a6f98d13d2f2c4f3. Summary of the ICC_{2.1} results are presented in Figure 3-5.

Figure 3 illustrates the ICC results for MP and KP identification

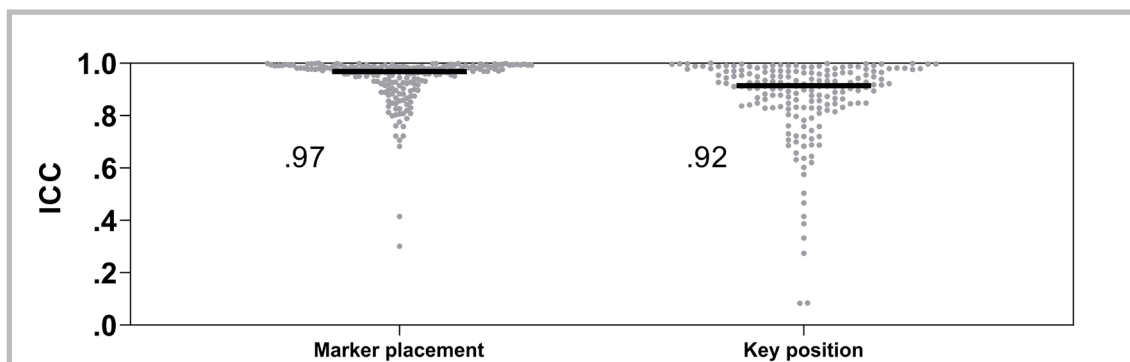


Figure 3. Summary of intraclass correlation coefficient results for kinematic variables from marker placement and key position identification reliability.

Notes. ICC – Intraclass Correlation Coefficient type 2.1. Values represent the median ICC across all variables. Each dot represents the ICC result for a specific variable. Red dots present the variables with the lowest reliability, also highlighted in the Supplementary materials A and B (https://osf.io/rzv8f/?view_only=fd0ea6ecf8a748e2a6f98d13d2f2c4f3)

Figure 4 illustrates the ICC results for kinematic variables from MP reliability, presented separately by variable conditions. ICC values ranged from .303, observed in the "Countermovement jump hip angle with dominant leg and SUB identification of KP in the frontal plane," to 1.00 in "SLD landing with dominant leg trunk inclination variable at SUB identification of KP for analysis in the frontal plane."

CV% values ranged from .6% to 54.9% in "SLBJ push off with dominant leg trunk angle variable at OBJ identification of KP for analysis in the frontal plane" and "SLCMJ with dominant leg trunk inclination variable at SUB identification of KP for analysis in the frontal plane," respectfully. Finally, SEM values ranged from .21° to 8.35° in "SLD landing with non-dominant leg trunk inclination variable at OBJ identification of KP for analysis in the frontal plane" and "SLCMJ with dominant leg trunk inclination variable at SUB identification of KP for analysis in the frontal plane," respectfully. Notably, ANOVA revealed statistically significant differences between the three repetitions in 8 out of 168 variables (Supplementary Material A, available at: https://osf.io/rzv8f/?view_only=fd0ea6ecf8a748e2a6f98d13d2f2c4f3). Figure 5 illustrates the ICC results for kinematic variables from KP identification reliability, presented separately by variable conditions. ICC values ranged from .083, observed in the "countermovement jump hip angle with non-dominant leg and SUB identification of KP in the frontal plane," to .99 in "SLD landing with dominant leg trunk inclination variable at SUB identification of KP for analysis in the frontal plane".

CV% values ranged from .6% to 38.1% in "SLD landing with dominant leg hip angle variable at SUB identification of KP for analysis in the frontal plane" and "SLBJ landing with non-dominant leg femur inclination variable at SUB identification

across the variables. The median ICC values for MP and KP were .971 and .922, respectively. Our findings indicate excellent reliability for kinematic variables obtained through MP and KP identification procedures, regardless of test type, plane of motion, leg dominance, or the method used to determine the KP. However, greater variability in ICC values was observed in the KP identification protocol across the variables.

Figure 4 illustrates the ICC results for kinematic variables from MP reliability, presented separately by variable conditions. ICC values ranged from .301, observed in the "Countermovement jump hip angle with dominant leg and SUB identification of KP in the frontal plane," to 1.00 in "SLD landing with dominant leg trunk inclination variable at SUB identification of KP for analysis in the frontal plane."

of KP for analysis in the frontal plane," respectfully. Moreover, SEM values ranged from .25° to 10.1° in "SLD landing with dominant leg trunk inclination variable at SUB identification of KP for analysis in the frontal plane" and "SLCMJ with non-dominant leg hip angle variable at SUB identification of KP for analysis in the frontal plane," respectfully. Notably, ANOVA revealed statistically significant differences between the three repetitions in 8 out of 178 variables (Supplementary Material B, available at: https://osf.io/rzv8f/?view_only=fd0ea6ecf8a748e2a6f98d13d2f2c4f3).

Discussion

2D kinematic analysis is a widely used method for assessing movement patterns. However, research confirming the reliability of MP and KP identification—both essential for the accuracy of this method—remains limited. The reliability of the method may be influenced by rater-dependent factors, such as inconsistencies in identifying KPs for analysis and MP, as well as variations in the execution of movement tasks. To the authors' knowledge, this is the first study to assess the reliability of manual MP and KP identification for analyzing movement techniques in single-leg jumps and landings. Specifically, the purpose was to evaluate the intra-session reliability of 2D kinematic variables related shin, thigh, and trunk segment inclinations relative to a vertical line and joint angles between segments two ways: (a) by calculating these variables from three separate repetitions of manual MP using Kinovea software, and (b) by calculating them from three repeated identifications of key movement positions during SLCMJ and SLD landing tests, as well as SLBJ push off and SLBJ landing phases.

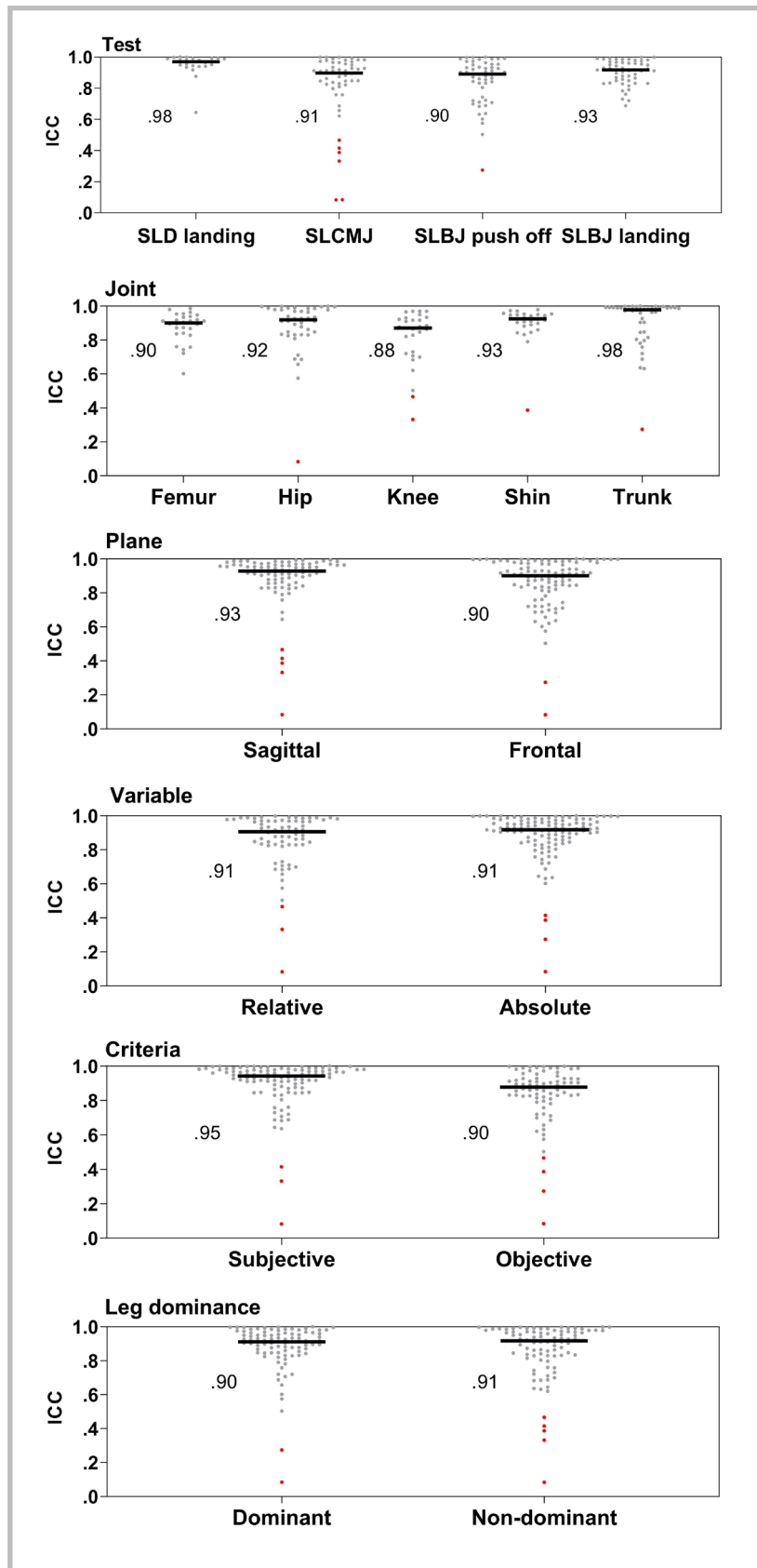


Figure 4. Summary of intraclass correlation coefficient results for kinematic variables from marker placement reliability, presented separately by variable conditions.

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. Red dots present the variables with the lowest reliability, also highlighted in the Supplementary material A (https://osf.io/rzv8f/?view_only=fd0ea6ecf8a748e2a6f98d13d2f2c4f3)

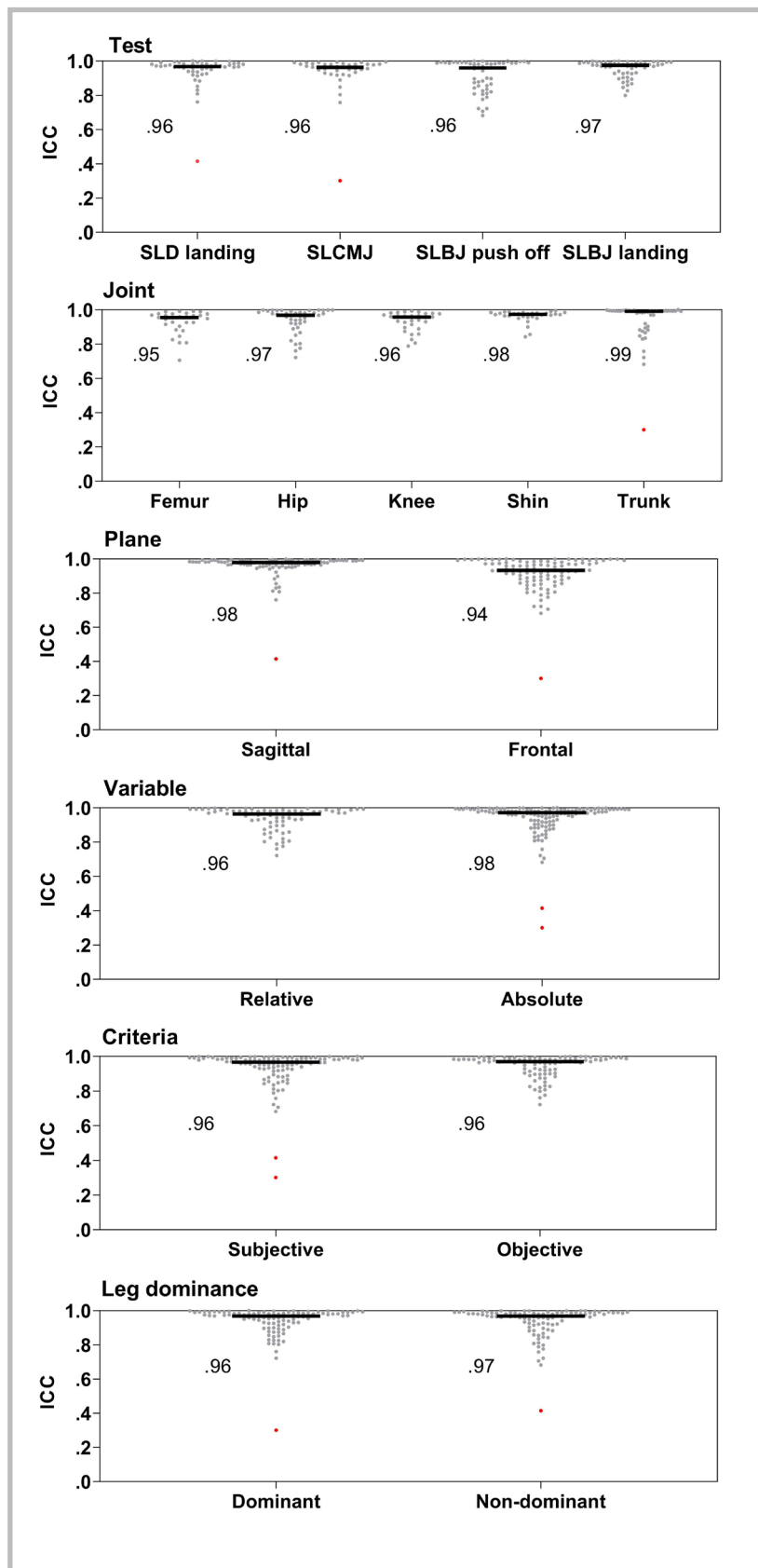


Figure 5. Summary of intraclass correlation coefficient results for kinematic variables from key position identification reliability, presented separately by variable conditions.

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. Red dots present the variables with the lowest reliability, also highlighted in the Supplementary material B (https://osf.io/rzv8f/?view_only=fd0ea6ecf8a748e2a6f98d13d2f2c4f3)

Overall, our findings demonstrate excellent reliability ($ICC > .900$) for both MP and KP identification protocols across most variables analyzed, aligning with our hypothesis. However, a few rare exceptions were observed. Median ICC values, regardless of variable conditions (Figures 3, 4, and 5), exceeded .883. These findings suggest that 2D kinematic analysis with manual MP can reliably assess lower extremity and trunk movement techniques during single leg jumps and landings, although researchers should be mindful of a few rare exceptions. For example, poor reliability in MP was observed for the amplitude variable in SLD landing with the non-dominant leg, when the key position was subjectively identified in the frontal plane ($ICC = .415$). Low ICC value may result from greater variability in movement control and stability when using the non-dominant leg, leading to inconsistent landing mechanics, making SUB identification of the markers more difficult. The second variable that showed poor reliability was "SLCMJ trunk inclination with dominant leg and SUB KP identification in the frontal plane" ($ICC = .301$). This may be attributed to the complexity of accurately assessing trunk inclination in the frontal plane, where segmental rotations are more pronounced and, therefore, identification of the markers more difficult.

Furthermore, our results show that practitioners can reliably use KP identification for kinematic analysis of SLCMJ, SLD landing, BJ push of and SLBJ landing, again with a few rare exceptions. This can help with kinematic analysis as these positions have been shown as moments in which injuries occur.^{9,10,17,18} Poor reliability in KP identification was found for the SLCMJ test non-dominant leg for the following variables: knee angle with SUB KP identification in the sagittal plane ($ICC = .332$), hip angle with SUB KP identification in the frontal plane ($ICC = .083$), and knee angle with OBJ KP identification in the sagittal plane ($ICC = .466$). Additionally, the variable "SLCMJ shin inclination with the non-dominant leg and SUB KP identification in the sagittal plane" exhibited low reliability ($ICC = .387$). Movements performed with the non-dominant leg often show greater variability due to weaker motor control²⁶ or reduced familiarity compared to the dominant leg. This could lead to greater variability in movement execution, especially during dynamic actions like jumps and landing. Furthermore, the SLBJ push off, "trunk inclination with the dominant leg and OBJ KP identification in the frontal plane" also showed poor reliability ($ICC = .274$). This may be attributed to rapid changes in posture (e.g., trunk rotation), which make it challenging to visually estimate the position of the marker.

Moreover, we report greater variability in KP (median $ICC = .921$) ICC values compared to MP (median $ICC = .973$). Greater variability in KP identification values could stem from the inherent challenges in consistently determining the exact time point of the analysis in dynamic tasks, such as jumps and landings. This variability may be influenced by subtle differences in individual movement patterns, slight discrepancies in manual MP, or the complexity of the movement itself. Additionally, factors like the observer's experience and the SUB nature of identifying KP can contribute to this inconsistency. However, we report a slightly lower reliability of OBJ ($ICC = .901$) compared to SUB ($ICC = .952$) KP identification. Despite these occasional variations, the overall reliability remains robust, suggesting that 2D kinematic analysis is a viable tool for assessing injury-prone moments, provided that standardized protocols are followed and potential sources of variability are acknowledged and addressed. This study results therefore demonstrate that the observed variability in results from the simplified 2D kinematic analysis is not due to rater-dependent error but is more likely attributable

to the individual technical execution of the movement tasks. Variability is a fundamental characteristic of human movement, often described as the normal variations that occur in motor performance during repeated executions of a task. According to dynamic systems theory, movement variability arises as biological systems self-organize in response to environmental, biomechanical, and morphological constraints, enabling the most stable movement execution.^{27,28} While biological variability cannot be eliminated—being dependent upon the individual's anatomical and physiological factors—it can be mitigated by improving the technical execution of jumps and landings, which necessitates the learning of the motor task. Increased variability poses challenges for statistical analysis and complicates the interpretation of results. Additionally, variability may also arise from factors such as equipment, the measurement environment, and the chosen sample. Therefore, future studies should follow the recommended guidelines in the current study, including paying attention to video quality, proper subject lighting, correct camera placement, and precise positioning of markers on bony anatomical landmarks to minimize the variability and to ensure the highest accuracy and reliability in 2D kinematic analysis MP and KP identification. Furthermore, 2D kinematics lacks of the ability to capture multi-plane motion, such as dynamic valgus. This could have compromised the external validity of our results. As such, some variables should be interpreted with caution.

Practical Applications

The high reliability of kinematic variables in MP and KP identification across various tests, planes, and conditions highlights the applicability of these methods in sports science and injury prevention. With median ICC values of .971 and .923 for MP and KP identification, respectively, these procedures can be confidently used in biomechanical assessments, rehabilitation monitoring, and performance analysis. The strengths of our study include a large sample size and a comprehensive analysis of multiple variables and movement tests. Furthermore, the method presented can be easily replicated by any practitioner, as the software for movement analysis is freely available. However, the current study has limitations that should be considered in future research. The manual MP process in Kinovea software was time-consuming, which reduces its practical applicability for analyzing movement techniques in larger groups of participants or entire sports teams. Future studies should identify the most sensitive variables for sport performance success (such as jump height or length) or those that are sensitive to injury risk minimization, in order to streamline the procedure and enhance its usefulness.

Conclusions

The results of this study significantly advance both research and practice by establishing a foundational understanding of the reliability of manual MP and KP identification in 2D kinematic analysis. The proposed simplified 2D kinematic analysis method maintains acceptable reliability for practical use in manual MP or KP identification, across all examined variables. To optimize reliability, adherence to the specified procedures is essential. These findings also demonstrate that manual 2D kinematic analysis can reliably assess lower extremity and trunk movement techniques during SLCMJ, SLD landing, SLBJ push off or SLBJ landing at selected KPs—either at the lowest vertical position of the greater trochanter or at the time point of the peak GRF. These results suggest that movement technique variability across multiple repetitions or between participants can be reliably

evaluated in practice or in the future studies using this proposed method.

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Ethical Committee approval

University of Ljubljana, Faculty of Sport Ethics Committee (reference number: 14:2023)

ORCID

Darjan Spudić ID <http://orcid.org/0000-0001-8353-2958>

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Conflicts of interest

The authors have no conflicts of interest to declare.

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Author-s contribution

Conceptualization, D.S., P.P. and N.Š.; methodology, D.S., P.P. and N.Š.; software, D.S. and N.Š.; validation, P.P. and N.Š.; P.P. and N.Š.; investigation, D.S, P.P. and A.R.; resources, P.P. and N.Š.; data curation, P.P. and N.Š.; writing—original draft preparation, A.R. and D.S.; writing—review and editing, A.R., D.S., P.P. and N.Š.; visualization, A.R. and D.S.; supervision, P.P. and N.Š.; project administration, P.P.; funding acquisition, D.S., P.P. and N.Š. All authors have read and agreed to the published version of the manuscript.

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Corresponding information:

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Correspondence to: Darjan Spudić PhD

University: Faculty of Sport, University of Ljubljana

Gortanova 22, 1000 Ljubljana, Slovenia

E-mail: darjan.spudic@fsp.uni-lj.si