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Reliability of the running vertical jump test in female team sport athletes

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ABSTRACT

Injury rates to the lower limb have increased over the past 40 years, coinciding with increases in female sport participation rates. Sport specific tests such as the running vertical jump (RVJ) are utilised for injury risk profiling, however the test-retest reliability is unknown.

Objectives: The aim of this study was to investigate the test-retest reliability of the thorax, pelvis and lower limb joint angular kinematics and kinetics for the RVJ test in female team sport athletes.

Design: Three-dimensional motion capture with force plate integration was utilised as participants performed five trials on each limb on three separate days.

Setting: Testing occurred in a biomechanics laboratory.

Participants: Thirty-four females (Australian Rules Football = 15, Netball = 12, Soccer = 7) participated in this study.

Main Outcome Measures: Intraclass correlation coefficients (ICC), effect sizes and typical errors (TE) of segment and joint angular kinematics and kinetics were calculated.

Results: Poor to excellent reliability (ICC = −0.12 − 0.92), small to large effect sizes (0.00–0.90) and TE (0.02–289.24) were observed across segment and joint angular kinematics and kinetics.

Conclusions: The RVJ test is recommended when analysing ground reaction forces and joint angular kinematics in female team sport athletes.

1. Introduction

Over the past 40 years, female participation rates across all levels of sport have increased, possibly contributing to increasing injury rates (Hecht & Arendt, 2014). Injuries result in multiple costs, such as rehabilitation, financial, long-term health, time-loss from work/education and sport (Hecht & Arendt, 2014). One of the most prevalent and devastating lower limb injuries is the rupture of the anterior cruciate ligament (ACL) where females are 9.2 times more likely than males to injure the ACL (Arundale et al., 2018; Fox et al., 2020). This gender disparity may be due to a number of factors such as an increased Q-angle, muscle imbalances and the dynamic knee valgus pattern (hip adduction, hip internal rotation, knee abduction, knee internal or external rotation and ankle eversion) (Alentorn-Geli et al., 2009; Carreiro & Lower, 2009; Hewett et al., 2005). Dynamic knee valgus, often observed in jumping/landing and change of direction-based sports, has been identified as a 'high-risk' action that contributes to lower limb injuries, such as soft tissue or joint injuries (Alentorn-Geli et al., 2009; Chinnasee et al., 2018; Hewett et al., 2005). To understand this movement pattern and identify those at greatest risk of injury, functional movement tests have been utilised. For example, biomechanical movement patterns within sport specific scenarios, such as the drop/depth jump, countermovement jump, change of direction, running vertical jump (RVJ) and/or hop tests have been the subject of investigation (Alentorn-Geli et al., 2009; Chinnasee et al., 2018; Hewett et al., 2005).

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The drop/depth jump was previously the most common functional movement test utilised within the sport setting to determine injury risk, focusing on the knee valgus position (Collings et al., 2019; Hewett et al., 2005). Previous investigation has seen intraclass correlation coefficients (ICC) as high as 0.98 for variables such as peak left and right hip flexion angle, indicating excellent test-retest reliability (Beardt et al., 2018; Ford et al., 2003; Mok et al., 2016). However, some reported reliability data may have been influenced by the design of the study. For example, small sample size (e.g. five participants), only two testing sessions with limited or no familiarisation potentially increasing the learning effect, and only performing reliability analysis on limited variables such as, between knee distance at maximum valgus (Ford et al., 2003) and knee or hip joint angular kinematics (Beardt et al., 2018; Mok et al., 2016). There is limited reliability data for all segment and joint angular kinematics, and joint ground reaction force (GRF) kinetics. Additionally, although the drop/depth jump was initially thought to provide some useful information regarding lower limb landing mechanics and potential for risk analysis, recently its usefulness has been questioned for assessment of injury risk such as the ACL injury, as it does not replicate the loading or movement patterns exhibited in dynamic sport situations (e.g. not multidirectional, unilateral or unanticipated, and from a standing start) (Beardt et al., 2018; Collings et al., 2019; Krosshaug et al., 2016). More multidirectional sport specific tests, such as the unanticipated change of direction and RVJ, have been increasingly examined (Chinnasee et al., 2018). The RVJ provides insight into an athlete's ability to jump and land unilaterally whilst reaching for an overhead object such as a ball (Morgan et al., 2014), and mimics sport specific scenarios (e.g. a marking action in Australian Rules Football (ARF) or catching a ball in Netball). Only six studies, to the authors knowledge, have investigated the RVJ test, where male and female team sport athlete populations such as Netball and ARF have been examined (Chinnasee et al., 2018; Dempsey et al., 2012; Fox et al., 2017; Fox, Bonacci, & Saunders, 2020; Morgan et al., 2014; Tai et al., 2018). To date, no studies have reported the test-retest reliability (consistency of a measure over multiple time points), and/or measurement error of this test, leaving questions regarding its potential clinical and high-performance sporting value or use. Confirming the test-retest reliability of the RVJ would give practitioners knowledge of the typical variability between sessions, and usefulness of the RVJ in injury risk assessment or return to sport protocols.

Therefore, the aim of this study was to identify the test-retest reliability of the thorax, pelvis and lower limb joint angular kinematics and kinetics for the RVJ test in female team sport athletes. Due to the variability of segment and joint angular kinematics and kinetics in previous RVJ investigations (Chinnasee et al., 2018; Dempsey et al., 2012; Fox et al., 2017; Fox, Bonacci, & Saunders, 2020; Morgan et al., 2014; Tai et al., 2018), it was hypothesised that the RVJ test-retest reliability would be moderate (ICC ≥0.5).

2. Methods

2.1. Participants

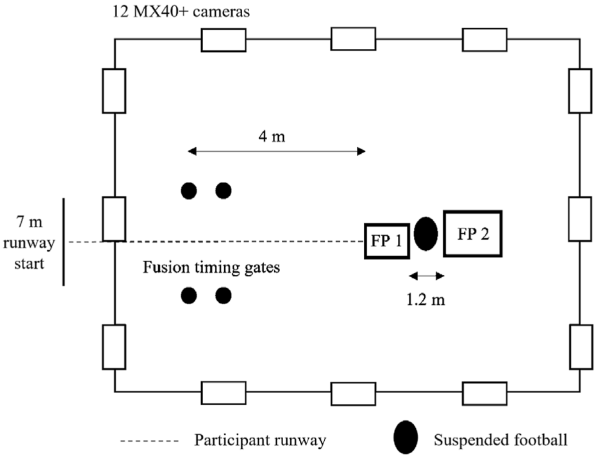
Thirty-four, female, team sport athletes (ARF = 15, Netball = 12, Soccer = 7) with a mean age ± standard deviation (SD) of 24.1 ± 4.2 yrs, height of 1.68 ± 0.08 m, and body mass of 67.8 ± 11.5 kg were recruited from South Australian sporting clubs (recreational to semi-professional). Based on prior work that reported an effect size of 0.3 for knee joint internal and external rotation kinematics (Chinnasee et al., 2018), a priori power analysis (G*Power v3.1, Düsseldorf, Germany) indicated a sample size of 20 was required (effect size 0.3, $p < 0.05$, power 0.8) to determine moderate reliability of tests (ICC ≥0.5) (Chinnasee et al., 2018). Inclusion criteria for participants included: aged between 16 and 35 yrs; minimum of 1 yr playing experience in their respective sport; no current or previous ACL injury; no history of lower extremity surgery; no current musculoskeletal injuries, chronic pain, or systemic condition; and no concussion within the 14 days prior to testing. Additionally, participants were screened via Stage 1 of the Exercise and Sports Science Australia Exercise Pre-Screening form to confirm their health status (Exercise and Sports Science Australia, 2019). This study was approved by the Human Research Ethics Committee with written informed consent obtained from all participants and/or a parent/legal guardian.

2.2. Experimental design

This study followed a repeated-measures cohort design. All testing was conducted during the pre-season period at a biomechanics laboratory. Participants completed three familiarisation sessions and three RVJ testing sessions to assess test-retest reliability (Hopkins et al., 2001). Due to the complexity of the RVJ test, three familiarisation sessions were conducted to minimise learnings effects and maximise familiarity and performance. The same investigator conducted each session to ensure consistent testing conditions and protocols. Each familiarisation and testing session were performed a minimum of 48 h apart, and participants were encouraged not to perform any strenuous physical activity 24 h prior to each session. Participants were instructed to wear minimal skin-tight clothing (e.g. sports bra and tight shorts) to minimise interference with reflective markers.

2.2.1. Familiarisation

The familiarisation sessions consisted of five RVJ trials per limb in accordance with the testing procedures (e.g. consistent entry velocity, foot placement, etc.). A dynamic warm-up was conducted prior to the RVJ trials, including 20 high knee skips, 10 leg swings (flexion/extension), 2 × 10 m runs at 50% of maximal speed, 2 × 10 m runs at 75% of maximal speed and 25 jumping jacks (modified from Manson et al. (2014)). A YardStick (Swift YardStick, Swift Performance, QLD, Australia) was used to determine the participants maximum RVJ height for both limbs. The highest result from the five trials within each familiarisation session was recorded for each limb as the participants 100% maximum RVJ height. Based upon this familiarisation protocol, the football was suspended at



FP = force plate.

Fig. 1. Laboratory set-up for the running vertical jump test.

90% of each participant's maximum RVJ height for the subsequent RVJ testing sessions (mean height 2.28 ± 0.12 m) (Fig. 1) (modified from Chinnasee et al., 2018).

2.3. Protocol

Upon arrival at the first familiarisation session, the participant's height and mass were measured using a wall mounted stadiometer (SECA 216, Seca, NY, USA) and scales (TANITA DR-953 Inner Scan, Tanita, Tokyo, Japan), respectively. The dominant limb was determined by asking each participant which leg they would kick a ball with (Walsh et al., 2012). The same warm-up as described for the familiarisation sessions was completed prior to testing.

2.4. Instrumentation

Reflective markers (38 × 14 mm) and additional clusters (2 thigh and 2 shank) were positioned on bony landmarks of the participants (upper, trunk, pelvis and lower body) based on the 6 degrees of freedom (6DOF) and IOR models (Fig. 2) (Cappozzo et al. 1995, 1997; Leardini et al., 2011). ASICS shoes (GT-2000, model 8) and socks were provided to every participant for standardisation. Twelve MX40+ VICON cameras captured movements at 200 Hz using the VICON Nexus software (v2.10, VICON, Oxford, UK) and were synchronised with two Kistler force plates (400 × 600 mm & 400 × 900 mm) (Kistler, Kistler Instruments Australia, VIC, Australia) recording at 2000 Hz. Prior to testing, cameras were calibrated following the VICON Nexus guidelines (Vicon Motion Systems, 2020). Fusion Timing Gates (Smartspeed, Fusion Sport, QLD, Australia) were positioned 3 and 4 m from the force platforms to calculate entry velocity (Fig. 1) (Sankey et al., 2020). Once reflective markers and clusters were attached, a static and range of motion (ROM) trial were captured at the commencement of each session, to calibrate and label reflective markers as recommended by VICON Nexus guidelines (Vicon Motion Systems, 2020). The ROM trial consisted of 10 x hip flexion/extensions, 10 x hip abduction/adductions, 10 x hip circumduction's and 10 x knee flexion/extensions for each limb.

2.4.1. Marker placement reliability

The primary investigator applied all reflective markers and undertook reliability of marker placement through two methods. Firstly, the primary investigator marked the location of the marker landmarks using a pen to the same participant on 10 different days. A co-investigator then marked the location of the landmarks to the same participant and the difference (mm) between landmarks was measured. Before commencement of testing, the primary investigator was required to have a difference of less than 5 mm for all marker locations on the final three consecutive days. Secondly, reflective marker placement using the static trials for each participant across sessions one, two and three were exported from VICON Nexus. The difference (mm) between selected lower body markers (e.g. greater trochanter, femoral lateral epicondyle, femoral medial epicondyle, head of fibula, lateral malleolus, medial malleolus, and tibial tuberosity) across the first 100 frames for the three vectors (X, Y, Z) were calculated for the left and right limbs. The mean difference for sessions one, two and three were used for statistical analysis.

2.4.2. RVJ test

Participants completed 10 x RVJ trials during each session, five on each limb. The order of limb trials was completed in a randomised order for each session, determined via a Random List Generator (Randomness and Integrity Services Ltd, Dublin, Ireland) computer program, to reduce anticipatory effects. Participants were required to run 7 m and pass through two timing gates at a standardised velocity of 14–16 km/h (4–6 m/s) (Chinnasee et al., 2018). They instructed to complete a single limb jump off the first force plate to reach a suspended ball, landing on the ipsilateral limb on the second force plate (Fig. 1) (Chinnasee et al.,

Fig. 2. Reflective marker and cluster (thigh & shank) placement based on 6DOF and IOR models.

2018). To be considered as a valid trial, the participant was required to run within the correct velocity range and land with the correct limb completely on each force plate. Participants were given a maximum of seven attempts to complete one trial successfully; where participants failed after seven attempts, the trial was reattempted at the end of the session. A minimum rest period of 1 min was provided between trials.

3. Data analysis

Static, ROM and RVJ trials were reconstructed and labelled, and gaps filled in VICON Nexus (v2.10.2, VICON, Oxford, UK) with C3D files exported for processing in Visual3D (v6.0, c-motion, MD, USA). Functional joint centres (hip and knee) were calculated using the ROM trials in Visual3D (C-Motion, 2020). A fourth order zero-lag low-pass Butterworth filter with 15 Hz cut-off frequency was used to smooth marker trajectory data. GRF (Fx, Fy, Fz), segment angular kinematics (thorax and pelvis) and joint angular kinematics (ankle, knee and hip) and joint kinetics (moment and power for the ankle, knee and hip) for the three axes of rotation (X = medial-lateral; Y = anterior-posterior; Z = longitudinal) were calculated. The thorax segment was defined as the axial rotation component of thorax motion relative to pelvis motion, otherwise known as 'X-Factor' in golf (Hume et al., 2005). Two key events were determined; initial contact (INC), defined as vertical GRF >10 N, and initial impact (INI), defined as 100 ms after INC (Norcross et al., 2013). Data was collected at these two time points for statistical analysis. Peak GRF metric for all three axes was exported for each trial. The data for the GRF, segment and joint angular kinematics and joint kinetics across the five trials were averaged for each session.

4. Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics software version 25 (IBM Corp, NY, USA). Mean and SD for RVJ testing sessions were calculated. All data was inspected through boxplots, identifying outliers in the dataset which were checked and corrected (if manual input error occurred). The Shapiro-Wilk goodness of fit test was used to check normality of the datasets. Data was not normally distributed for the right trial thorax and pelvis segment angular kinematics. Therefore, differences between sessions (e.g. 1 vs. 2, 1 vs. 3, 2 vs. 3) for right limb RVJ trial segment kinematics were identified through the Friedman non-parametric and post-hoc Wilcoxon signed-rank tests. Repeated measures ANOVA and post-hoc, pairwise comparisons with a Bonferroni correction identified between-session differences (e.g. 1 vs. 2, 1 vs. 3, 2 vs. 3) for all other segment and joint kinematic and kinetic data, presented in the supplementary material tables. Test-retest reliability of reflective marker placement and all kinematic and kinetic data was assessed through $ICC_{3,1}$ where values < 0.50 were interpreted as poor, 0.50–0.75 as moderate, 0.75–0.90 as good and >0.90 as excellent (Portney & Watkins, 2009). Effect size (ES) (thresholds set as small = 0.2, moderate = 0.6, large = 1.2, very large = 2.0 and nearly perfect = 4.0) and typical error (TE) were calculated to represent magnitude of difference between sessions, and magnitude of error, respectively (Hopkins, 2015; Smith & Hopkins, 2011). TE was calculated by dividing the SD of the difference score by square root 2 (Hopkins, 2015). Mean and between-session (e.g. 1 vs. 2, 1 vs. 3, 2 vs. 3) ICC and TE are presented (Tables S1–S13). The significance level was set at $p < 0.05$ for all analyses.

5. Results

All participants completed the testing protocol successfully without reporting pain or discomfort. Right limb dominance was reported by 91.0% of participants (31), whereas left limb dominance was reported by 9.0% of participants (3). Only one participant was unsuccessful in completing a valid trial during a testing session, exceeding the seven attempts allowed. This trial was repeated at the end of the testing session and successfully completed. Each session consisted of 10 RVJ trials where on average, 2.2 trials were failed in session 1, 1.4 trials were failed in session 2 and 0.7 trials were failed in session 3.

5.1. Marker reliability

Primary investigators' mean test-retest reliability of marker placement for the left and right limbs was moderate to good (ICC = 0.73–0.80) where mean TE was lower for the vectors Y and Z, and higher for X (Tables S1 and S2).

5.2. Reliability at INC

5.2.1. Segment angular kinematics

Mean test-retest reliability at INC of the left limb RVJ thorax and pelvis segments demonstrated poor to moderate ICCs (0.20–0.52) for all axes of rotation. No differences were found between sessions for the thorax in all three axes. Pelvic obliquity (Y) was 10.3° greater in session one compared with session two ($p = 0.01$) and pelvic rotation (Z) was 12.2° greater in session one compared with session two ($p = 0.02$). The thorax and pelvis mean TE were lower for the medial-lateral and anterior-posterior axes, and higher for the longitudinal axis with small ES (0.00–0.13) (Table S3).

Mean test-retest reliability at INC of the right limb RVJ thorax and pelvis segments demonstrated poor to moderate ICCs (0.34–0.57) for all axes of rotation. No differences were found between sessions for the thorax in all three axes. Pelvic rotation (Z) was 13.0° greater in session one compared with session two and 6.4° greater in session three compared with session two ($p = 0.01$). The thorax and pelvis mean TE were lower for the medial-lateral and longitudinal axes, and higher for the anterior-posterior axis (Table S4).

5.2.2. Joint angular kinematics

Mean test-retest reliability at INC of the left limb RVJ ankle, knee and hip joints demonstrated moderate to good ICCs (0.53–0.86) for all axes of rotation. Ankle inversion (Y) was 2.6° greater in session one compared with sessions two and three ($p = 0.01$). No differences were found between sessions for the knee joint in all three axes. Hip flexion (X) was 4.3° greater in session one compared with session two ($p = 0.01$). The ankle, knee, and hip joint mean TE were lower for the longitudinal and anterior-posterior axes, and higher for medial-lateral axis with small ES (0.00–0.19) (Table S5).

Mean test-retest reliability at INC of the right limb RVJ ankle, knee and hip joints demonstrated poor to excellent ICCs (0.27–0.92) for all axes of rotation. No differences were found between sessions for the ankle, knee, and hip joints in all three axes. The ankle, knee, and hip joint mean TE were lower for the longitudinal and anterior-posterior axes, and higher for medial-lateral axis with small ES (0.01–0.05) (Table S5).

5.2.3. Joint kinetics

Mean test-retest reliability at INC of the left limb RVJ peak GRF demonstrated good ICCs (0.83–0.87) for all axes of rotation. Session 1 GRF was 220.4 N greater than session two, and 251.6 N greater than session three in the medial-lateral axis ($p = 0.01$). The GRF mean TE were lower for the longitudinal and anterior-posterior axes, and higher for the medial-lateral axis with small ES (0.05–0.19). Mean test-retest reliability at INC of the right limb RVJ peak GRF demonstrated good to excellent ICCs (0.82–0.91) for all axes of rotation. Session 1 GRF was 180.2 N greater than session two in the medial-lateral axis ($p = 0.03$), and session two was 15.5 N greater than session three in the anterior-posterior axis ($p = 0.03$). The GRF mean TE were lower for the longitudinal and anterior-posterior axes, and higher for the medial-lateral axis with small ES (0.08–0.13) (Table S6).

Mean test-retest reliability at INC of the left and right limb RVJ joint moments demonstrated poor ICCs (left −0.12 − 0.36, right −0.02 − 0.37). No differences were found between sessions for the ankle, knee, and hip joint moments in all three axes. The joint moment mean TE were lower for the longitudinal axis and higher for the medial-lateral and anterior-posterior axis with small ES (0.00–0.06) (Table S7).

Mean test-retest reliability at INC of the left and right limb RVJ joint powers demonstrated poor to moderate ICCs (left −0.01 − 0.16, right −0.02 − 0.58). No differences were found between sessions for the ankle, knee, and hip joint powers in all three axes. The joint power mean TE were lower for the medial-lateral and longitudinal axes, and higher for the anterior-posterior axis with small ES (0.00–0.50) (Table S8).

5.3. Reliability at INI

5.3.1. Segment angular kinematics

Mean test-retest reliability at INI of the left limb RVJ thorax and pelvis segments demonstrated poor to moderate ICCs (0.28–0.74) for all axes of rotation. No differences were found between sessions for the thorax in all three axes. Pelvic obliquity (Y) was 15.0° greater in session one compared with session two ($p = 0.02$) and pelvic rotation (Z) was 19.0° greater in session one compared with session three ($p = 0.05$). The thorax and pelvis mean TE were lower for the medial-lateral and anterior-posterior axes, and higher for the longitudinal axis with small ES (0.01–0.11) (Table S9).

Mean test-retest reliability at INI of the right limb RVJ thorax and pelvis segments demonstrated poor to moderate ICCs (0.34–0.70) for all axes of rotation. Thorax obliquity (Y) was 4.3° greater in session one compared with session two, and 2.2° greater in session three compared with session one ($p = 0.04$). Pelvic rotation (Z) was 16.8° greater in session one compared with session two and 13.5° greater in session three compared with session two ($p = 0.05$). The thorax and pelvis mean TE were lower for the medial-lateral and longitudinal axes, and higher for the anterior-posterior axis (Table S10).

5.3.2. Joint angular kinematics

Mean test-retest reliability at INI of the left limb RVJ ankle, knee and hip joints demonstrated moderate to good ICCs (0.59–0.76) for all axes of rotation. No differences were found between sessions for the ankle and knee joints in all three axes. Hip flexion (X) was 6.3° greater in session one compared with session two, and session two was 4.2° lower than session three ($p = 0.01$). The ankle, knee and hip mean TE were lower for the longitudinal and anterior-posterior axes, and higher for the medial-lateral axis with small ES (0.00–0.20) (Table S11).

Mean test-retest reliability at INI of the right limb RVJ ankle, knee and hip joints demonstrated poor to moderate ICCs (0.42–0.79) for all axes of rotation. No differences were found between sessions for the ankle, knee, and hip joints in all three axes. The ankle, knee and hip mean TE were lower for the longitudinal and anterior-posterior axes, and higher for the medial-lateral axis with small ES (0.00–0.04) (Table S11).

5.3.3. Joint kinetics

Mean test-retest reliability at INI of the left and right limb RVJ ankle, knee and hip joint moments demonstrated poor to good ICCs (left 0.01–0.62, right 0.00–0.80) for all axes of rotation. No differences were found between sessions for the ankle, knee, and hip joints in all three axes. The ankle, knee and hip mean TE were lower for the longitudinal and anterior-posterior axes, and higher for the medial-lateral axis with small ES (0.00–0.04) (Table S12).

Mean test-retest reliability at INI of the left and right limb RVJ ankle, knee and hip joint powers demonstrated poor to moderate ICCs (left 0.00–0.41, right 0.12–0.72) for all axes of rotation. No differences were found between sessions for the ankle, knee and hip joints in all three axes. The ankle, knee and hip mean TE were lower for the medial-lateral and longitudinal axes, and higher for the anterior-posterior axis with small ES (0.01–0.05) (Table S13).

6. Discussion

The aim of this study was to investigate the test-retest reliability of segment and joint angular kinematics and kinetics for the RVJ test in female team sport athletes where moderate reliability (ICC ≥0.5) was hypothesised. Contrary to our hypothesis, poor to excellent test-retest reliability was identified for segment and joint angular kinematics (ICC = 0.20–0.92) and kinetics (ICC = −0.12 − 0.80) across the three axes of rotation with small ES (0.00–0.50) and TE ranging from 0.02 to 289.24, across segment and joint angular kinematics and kinetics. The RVJ test may be of limited use by practitioners when analysing the thorax and pelvis segment angular kinematics, joint moments and powers at INC and INI for injury risk assessment in female team sport athletes, due to lower reliability and higher TE outcomes. Therefore, it is recommended to utilise this test when investigating GRF and joint angular kinematics of the hip, knee and ankle at INC and INI, due to higher reliability and lower TE outcomes. These conclusions can assist in the informed selection of injury risk profiling tests for different clinical or high-performance sport populations.

Previously, the drop/depth jump was considered one of the most important functional movement tests in identifying dynamic knee valgus, considered a marker of injury risk (Hewett et al., 2005). With excellent test-retest reliability reported for this assessment repeatedly, it was relied on for important clinical and high-performance sport analyses (Beardt et al., 2018; Ford et al., 2003; Mok et al., 2016). However, the drop jump task is not sport specific and may not be relevant for injury risk assessment such as the ACL injury (Collings et al., 2019; Krosshaug et al., 2016). For example, Kristianslund and Krosshaug (2013) determined poor correlation of knee abduction moments to the sidestep cutting task where knee moments were six times higher than those during the drop jump. With the RVJ test being recent in examination, this is the first study to identify the TE and test-retest reliability of the assessment. In comparison to TE observed during the drop jump test, some similar outcomes can be seen. Mok et al. (2016) investigated the drop jump in female Handball and Soccer athletes where excellent reliability was observed for all variables. At INC, TE of the right knee flexion/extension angle for the drop jump was 2.40° (Mok et al., 2016) and RVJ test 3.00°. At INC, TE of the right knee abduction/adduction angle for the drop jump was 1.11° (Mok et al., 2016) and RVJ test 2.51°. At INC, TE of the right knee internal/external rotation angle for the drop jump was 1.58° (Mok et al., 2016) and RVJ test 6.23°. Further, some similar reliability outcomes between the drop jump test and RVJ can be observed, particularly for the knee joint angular kinematics (Beardt et al., 2018; Mok et al., 2016). Beardt et al. (2018) investigated the drop jump in female Volleyball athletes where ICCs as high as 0.98 were reported. At INC, reliability of the right and left knee flexion angle for the drop jump was 0.88 and 0.76 (Beardt et al., 2018) and RVJ test 0.63 and 0.67, respectively. At INC, reliability of the right and left hip flexion angle for the drop jump was 0.92 and 0.94 (Beardt et al., 2018) and RVJ test 0.39 and 0.53, respectively. Therefore, when comparing specific kinematics of the drop jump and RVJ test, it is obvious the RVJ is not as reliable as the drop jump where TE are similar. Lower reliability outcomes were observed specifically for the RVJ trunk and pelvis segment angular kinematics, joint powers, and moments at both INC and INI time points. This may be due to the complexity of the task itself, the laboratory set up or variability of the testing population.

Previous investigation of the RVJ functional movement test has been performed for athletic male (Dempsey et al., 2012; Fox et al., 2017; Fox, Bonacci, & Saunders, 2020; Morgan et al., 2014; Tai et al., 2018) and female populations (Chinnasee et al., 2018) where no test-retest reliability was reported. Despite this lack of reliability reporting, some similar kinematic and kinetic outcomes to the current study were observed by Chinnasee et al. (2018) and Morgan et al. (2014), investigating female field hockey and male ARF athletes, respectively. Chinnasee et al. (2018) investigated the RVJ, unplanned sidestep, single leg drop jump and single leg countermovement jump in one testing session. Compared to the current study, the dominant limb hip (mean difference X = 7.0, Y = −22.1, Z = −24.9°), knee (mean difference X = −5.2, Y = −0.2, Z = 22.0°) and ankle (mean difference X = −10.0, Y = −19.8, Z = −24.5°) joint angular kinematics at INC differed. Additionally, the dominant limb hip (mean difference X = 0.3, Y = −0.7, Z = 0.8 N m/kg), knee (mean difference X = 8.2, Y = 0.6, Z = −0.4 N m/kg), and ankle (mean difference X = 0.3 N m/kg) joint moments at INI differed compared with the current study. Morgan et al. (2014) investigated the RVJ within one testing session, reporting angular kinematics and joint moments for the right limb. Compared to the current study, the right hip (mean difference X = −7.9, Y = 14.8, Z = 2.0°), knee (mean difference X = −7.6, Y = −0.7, Z = 1.4°) and ankle (mean difference X = 4.5°) joint angular kinematics at INI differed. Additionally, the right hip (mean difference X = 1.4, Y = −0.7, Z = 0.4 N m/kg), knee (mean difference X = 7.2, Y = 1.1, Z = −0.5 N m/kg), and ankle (mean difference X = 1.4 N m/kg) joint moments at INI also differed. The differences in kinematics and kinetics between the current and prior RVJ investigations may be due to differences in testing protocols (e.g. number of sessions, number of trials, familiarisation) or population (e.g. competition level, sport, training age, gender).

The knee joint moments were previously reported as important variables when investigating injury risk, particularly the ACL injury (Alentorn-Geli et al., 2009; Hewett et al., 2005). Injuries such as these occur during dynamic, multi-planar movements where kinematic and kinetic movement patterns across the three axes of rotation contribute in some way to the injury, for example dynamic knee valgus (Alentorn-Geli et al., 2009). The anterior-posterior axis, particularly for the knee joint, has been extensively investigated where previous ‘high-risk’ thresholds (>8.4 N m/kg at INC (Hewett et al., 2005) and +1.6 SD above the mean (Chinnasee et al., 2018)) have been proposed for the female athlete population. Hewett et al. (2005) determined this ‘high-risk’ threshold from the drop vertical jump test in female Soccer, Volleyball, and Basketball athletes through a prospective study design. In contrast, Chinnasee et al. (2018) performed the RVJ test (named single-leg jump-landing) in female Field Hockey athletes, determining ACL injury risk classification based on peak knee abduction and internal rotation moments. Based on outcomes that exceeded proposed ‘normal’ variability thresholds, prior studies have categorised these athletes as ‘high-risk’ for prospective injury (Chinnasee et al., 2018; Hewett et al., 2005). Caution must be advised when reviewing ‘high-risk’ thresholds from research that has not clearly identified the test-retest reliability of assessment protocols. In the current study, knee moments at INI demonstrated poor to moderate test-retest reliability (0.02–0.72) with some TE up to four times the mean. This demonstrates that for the RVJ test, knee moments demonstrate poor to moderate reliability and therefore may not be reliable in determining injury risk. The current study has extended prior work by highlighting the normal variability of RVJ segment and joint angular kinematics and kinetics for the female athlete population with a blanket ‘high-risk’ threshold proving inappropriate and potentially inaccurate. The variability from additional factors such as equipment and protocol set-up errors must also be taken into consideration during injury risk assessments.

Prior studies analysing the RVJ have not included familiarisation sessions to reduce potential learning effects, or ROM trials to determine joint centres or marker placement reliability (Chinnasee et al., 2018; Dempsey et al., 2012; Fox et al., 2017; Fox, Bonacci, & Saunders, 2020; Morgan et al., 2014; Tai et al., 2018). These aspects of methodological design may influence the kinematic and kinetic data, (e.g. performing one testing session may not provide a true representation of an individual's movement patterns). The current study aimed to address these methodological concerns by including three familiarisation sessions, three testing sessions for the reliability analysis, and reporting reliability outcome measures (e.g. ICCs, ES and TE). Additionally, ROM trials were performed and marker placement reliability were conducted. Marker placement is a primary source of between-session variability due to soft tissue artefact (i.e. movement of muscle, fat and skin beneath markers causing displacement) and human error (Cappozzo et al., 1995; Gorton et al., 2009). In the current study, the primary investigator exhibited moderate to good reliability (Tables S1 and S2) with kinematic and kinetic differences between sessions likely due to intra-subject variability rather than marker placement errors. These aspects of methodological design must be considered and minimised to accurately interpret the degree of individual variability between sessions, and subsequent use of the RVJ for injury risk profiling. Therefore, despite the inclusion of three familiarisation sessions, variable test-retest reliability, ES and TE were detected across a multitude of kinematic and kinetic variables. This demonstrates that the RVJ test may be of limited use by practitioners when analysing the thorax and pelvis segment angular kinematics, joint moments and powers at INC and INI in this female team sport athlete population.

This is the first study to assess the RVJ test and utilise three familiarisation sessions, three testing sessions, report marker placement reliability outcomes and normative data for the female team sport athlete population. A limitation of the current study is the variable competition level across the female athletes which may influence the outcomes of this study. Future investigations are directed to compare sports, movement patterns, competition level and strength profiles of female athletes. Identifying these in future research will broaden the current normative data for the female team sport athlete population, and determine what, if any value they offer in injury risk profiling, rehabilitation monitoring and return to sport protocols.

7. Conclusion

To our knowledge, this is the first study to utilise familiarisation sessions, three testing sessions and report reliability outcomes for the RVJ test. It provided an accurate representation of the variability within the kinematic and kinetic profiles for the female athlete population within a sport-specific task. The RVJ test may be of limited use by practitioners when analysing the thorax and pelvis segment angular kinematics, joint moments and powers at INC and INI in female team sport athletes, due to lower reliability and higher

TE outcomes. Therefore, it is recommended to utilise this test when investigating GRF and joint angular kinematics of the hip, knee and ankle at INC and INI, due to higher reliability and lower TE outcomes. These conclusions can assist in the informed selection of injury risk profiling tests for different clinical or high-performance sport populations.

Ethical approval

This study was approved by the Human Research Ethics Committee with written informed consent obtained from all participants and/or a parent/legal guardian.

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Declaration of competing interest

The authors report no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2023.01.005.

Manuscript Submission Conflict of Interest File.

References

Alentorn-Geli, E., Myer, G., Silvers, H., Samitier, G., Romero, D., Lázaro-Haro, C., & Cugat, R. (2009). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surgery, Sports Traumatology, Arthroscopy, 17*(7), 705–729.

Arundale, A., Silvers-Granelli, H., & Snyder-Mackler, L. (2018). Career length and injury incidence after anterior cruciate ligament reconstruction in major league soccer players. *Orthopaedic Journal of Sports Medicine, 6*(1), 1–8.

Beardt, B., McCollum, M., Hinshaw, T., Layer, J., Wilson, M., Zhu, Q., & Dai, B. (2018). Lower-extremity kinematics differed between a controlled drop-jump and volleyball-takeoffs. *Journal of Applied Biomechanics, 34*(4), 327–335.

C-Motion. (2020). *Functional joints, C-motion wiki documentation*. viewed 10 September 2020 https://c-motion.com/v3dwiki/index.php?title=Functional_Joints.

Cappozzo, A., Cappello, A., Croce, U., & Pensalfini, F. (1997). Surface-marker cluster design criteria for 3-D bone movement reconstruction. *IEEE Transactions on Biomedical Engineering, 44*(12), 1165–1174.

Cappozzo, A., Catani, F., Della Croce, U., & Leardini, A. (1995). Position and orientation in space of bones during movement: Anatomical frame definition and determination. *Clinical Biomechanics, 10*(4), 171–178.

Carreiro, J., & Lower, L.' (2009). In C. Wilson, & B. Simmons (Eds.), *Pediatric manual medicine* (1 edn, pp. 273–327). Churchill Livingstone Elsevier Limited.

Chinnasee, C., Weir, G., Sasimontonkul, S., Alderson, J., & Donnelly, C. (2018). A biomechanical comparison of single-leg landing and unplanned sidestepping. *International Journal of Sports Medicine, 39*(8), 636–645.

Collings, T., Gorman, A., Stuelcken, M., Mellifont, D., & Sayers, M. (2019). Exploring the justifications for selecting a drop landing task to assess injury biomechanics: A narrative review and analysis of landings performed by female netball players. *Sports Medicine, 49*(3), 389–395.

Dempsey, A., Elliott, B., Munro, B., Steele, J., & Lloyd, D. (2012). Whole body kinematics and knee moments that occur during an overhead catch and landing task in sport. *Clinical Biomechanics, 27*(5), 466–474.

Exercise and Sports Science Australia. (2019). *Adult pre-exercise screening system (APSS)*, Exercise and sports science Australia. viewed 13 July 2021 https://www.essa.org.au/Public/ABOUT_ESSA/Pre-Exercise_Screening_Systems.aspx.

Ford, KR, Myer, GD, & Hewett, TE (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine & Science in Sports & Exercise, 35*(10), 1745–1750.

Fox, A., Bonacci, J., Hoffmann, S., Nimphius, S., & Saunders, N. (2020). Anterior cruciate ligament injuries in Australian football: Should women and girls be playing? You're asking the wrong question. *BMJ Open Sport & Exercise Medicine, 6*(1), 1–3.

Fox, A., Bonacci, J., McLean, S., & Saunders, N. (2017). Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. *Scandinavian Journal of Medicine & Science in Sports, 27*(5), 525–534.

Fox, A., Bonacci, J., & Saunders, N. (2020). The relationship between performance of a single-leg squat and leap landing task: Moving towards a netball-specific anterior cruciate ligament (ACL) injury risk screening method. *Sports Biomechanics, 19*(4), 493–509.

Gorton, G., Hebert, D., & Gannotti, M. (2009). Assessment of the kinematic variability among 12 motion analysis laboratories. *Gait & Posture, 29*(3), 398–402.

Hecht, S., & Arendt, E. (2014). Training the female athlete. In M. Mountjoy (Ed.), *Handbook of sports medicine and science: The female athlete* (pp. 1–8). Hoboken, NJ, USA: John Wiley & Sons, Inc. Hoboken, NJ, USA.

Hewett, T., Myer, G., Ford, K., Heidt, R., Colosimo, A., McLean, S., van Den Bogert, A., Paterno, M., & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes a prospective study. *The American Journal of Sports Medicine, 33*(4), 492–501.

Hopkins, W. (2015). Spreadsheets for analysis of validity and reliability. *Sportscience, 19*. viewed 24 October 2020 https://sportsci.org/2015/ValidRely.htm.

Hopkins, W., Schabort, E., & Hawley, J. (2001). Reliability of power in physical performance tests. *Sports Medicine, 31*(3), 211–234.

Hume, P., Keogh, J., & Reid, D. (2005). The role of biomechanics in maximising distance and accuracy of golf shots. *Sports Medicine, 35*(5), 429–449.

Kristianslund, E., & Krosshaug, T. (2013). Comparison of drop jumps and sport-specific sidestep cutting implications for anterior cruciate ligament injury risk screening. *The American Journal of Sports Medicine, 41*(3), 684–688.

Krosshaug, T., Steffen, K., Kristianslund, E., Nilstad, A., Mok, K., Myklebust, G., Andersen, T., Holme, I., Engebretsen, L., & Bahr, R. (2016). The vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players: A prospective cohort study of 710 athletes. *The American Journal of Sports Medicine, 44*(4), 874–883.

Leardini, A., Biagi, F., Merlo, A., Belvedere, C., & Benedetti, M. (2011). Multi-segment trunk kinematics during locomotion and elementary exercises. *Clinical Biomechanics, 26*(6), 562–571.

Manson, S., Brughelli, M., & Harris, N. (2014). Physiological characteristics of international female soccer players. *The Journal of Strength & Conditioning Research, 28*(2), 308–318.

Mok, K., Petushek, E., & Krosshaug, T. (2016). Reliability of knee biomechanics during a vertical drop jump in elite female athletes. *Gait & Posture, 46*, 173–178.

Morgan, K., Donnelly, C., & Reinbolt, J. (2014). Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing: Implications for anterior cruciate ligament injury risk. *Journal of Biomechanics, 47*(13), 3295–3302.

Norcross, M., Lewek, M., Padua, D., Shultz, S., Weinhold, P., & Blackburn, T. (2013). Lower extremity energy absorption and biomechanics during landing, part I: Sagittal-plane energy absorption analyses. *Journal of Athletic Training, 48*(6), 748–756.

Portney, L., & Watkins, M. (2009). *Foundations of clinical research: Applications to practice* (3rd ed.). Upper Saddle River, New Jersey: Pearson/Prentice Hall.

Sankey, S., Robinson, M., & Vanrenterghem, J. (2020). Whole-body dynamic stability in side cutting: Implications for markers of lower limb injury risk and change of direction performance. *Journal of Biomechanics, 104*, 1–9.

Smith, T., & Hopkins, W. (2011). Variability and predictability of finals times of elite rowers. *Medicine & Science in Sports & Exercise, 43*(11), 2155–2160.

Tai, W., Wang, L., & Peng, H. (2018). Biomechanical comparisons of one-legged and two-legged running vertical jumps. *Journal of Human Kinetics, 64*(1), 71–76.

Vicon Motion Systems. (2020). *Vicon Nexus user guide*. Oxford, UK: Vicon Motion Systems Limited.

Walsh, M., Boling, M., McGrath, M., Blackburn, T., & Padua, D. (2012). Lower extremity muscle activation and knee flexion during a jump-landing task. *Journal of Athletic Training, 47*(4), 406–413.