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Reliability, validity, and maturation-related differences of frontal and sagittal plane landing kinematic measures during drop jump and tuck jump screening tests in male youth soccer players

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ABSTRACT

Objectives: To determine the inter-rater and intra-rater reliability of frontal and sagittal plane landing kinematic measures during drop jump (DVJ) and tuck jump (TJA) tasks in male youth soccer players, to assess the concurrent validity between DVJ and TJA tests, and to evaluate the ability of both tasks to detect differences between players' stage of maturation.
Design: Cross-sectional study.
Participants: 223 male youth soccer players.
Main outcome measures: Frontal plane knee projection angles (FPPA), and hip (HF), knee (KF) and ankle (AF) flexion angles at initial contact (IC) and peak flexion (PF) (i.e., the deepest landing position) in the sagittal plane were assessed.
Results: Good-to-excellent inter- and intra-rater reliability (ICC > 0.75; $TEM_{ST} < 0.3$; $CV_{TE} < 5\%$) for the FPPA, HF and KF during DVJ and TJA tasks were found. A low concurrent validity between DVJ and TJA measures was reported. Differences by maturity status ($BF_{10} > 10$; error < 10; $\delta > 0.6$) were only identified for the TJA. Pre-PHV group reported higher FPPA, HF-IC, HF-PF, and KF-IC values, as well as lower AF-IC than post-PHV. Pre-PHV also displayed greater HF-IC and KF-IC than circa-PHV group.
Conclusions: Although both tests are reliable, the TJA might be viewed as a more informative tool given it shows greater FPPA and can also detect differences by maturity status.

1. Introduction

Young team sport players are at risk of knee and ankle injuries (Jones et al., 2019; Owoeye et al., 2020). Neuromuscular control has been associated with this increased risk (Quatman-Yates et al., 2012; Read et al., 2016a), and screening may be useful to identify players with altered movement patterns (Fort-Vanmeerhaeghe et al., 2016). Most studies analysing landing technique have mainly focused on frontal plane kinematic measures (Dingenen et al., 2015). Knee medial displacement (dynamic valgus) has shown to increase the magnitude of loads experienced by medial collateral (MCL) and anterior cruciate ligaments (ACL), and hence predispose knee injuries (Hewett et al., 2004; Yu & Garrett, 2007). Higher valgus angles have been displayed by younger male soccer players in periods prior to and around the peak height velocity (PHV) compared to older youths (Lloyd et al., 2019; Read et al., 2018a), demonstrating an interaction effect between landing mechanics and maturation. Furthermore, it has been suggested that the appearance of dynamic knee valgus might be influenced by deficits in sagittal plane motions (Dingenen et al., 2015; Pollard et al., 2010). Reduced hip, knee and ankle flexion patterns may contribute to knee valgus as a compensatory strategy that modulates the greater ground reaction forces derived from a stiffer landing posture (Dingenen et al., 2015; Pollard et al., 2010;

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Shimokochi et al., 2013).

To investigate the kinematics of landing tasks, a broad range of tests have been used in previous literature and the drop vertical jump (DVJ) has been a popular test choice (Pedley et al., 2020). The assessment of landing kinematic measures from a cost-effectiveness approach (through 2-dimensional video cameras) in DVJ tasks has shown to be reliable (intra- and inter-rater intra-class correlation coefficients [ICC] > 0.89) (Mizner et al., 2012; Ortiz et al., 2016), providing a suitable field-based test for kinematic screening into clinical practice. However, while a number of studies have found some relationships between DVJ biomechanics and the risk of sustaining knee injuries (e.g., ACL) (Hewett et al., 2005; Padua et al., 2015), other investigations have failed in making these associations (Krosshaug et al., 2016; Räisänen et al., 2020). These inconsistent results together with the questionable external validity of a test which entails a drop from a standard height (Lloyd et al., 2019; Read et al., 2016b) have led to the emergence of new protocols with performances closer to the competitive practice.

Myer et al. (2008) proposed the tuck jump assessment (TJA). This test consists of repeated tuck jumps during a 10-s period while a rater visually grades jumping and landing mechanics. The TJA may offer clinical advantages over the DVJ test. For instance, in this protocol the participant starts and stops from ground level instead of dropping from a box, better representing techniques encountered in sport (Read et al., 2016b). In the original TJA protocol, movement mechanics were qualitatively rated using a 10-item scoring sheet (Myer et al., 2008). More recently, quantitative assessment of important kinematic markers during the TJA, such as dynamic valgus (through frontal plane projection angles [FPPA]), has increased (Lloyd et al., 2019, 2020; Read et al., 2018a), probably led by the large variation in reliability results documented for the neuromuscular outcomes obtained through TJA using the traditional (dichotomous [0 or 1]) and modified (polychotomous [0, 1 or 2]) 10-item scoring systems (Gokeler & Dingenen, 2019; Lindblom et al., 2021; Racine et al., 2021). While some reliability data has been reported for kinematic analysis of FPPA (Lloyd et al., 2019; Read et al., 2018a), more research is needed to determine the reliability of kinematic assessments beyond just the knee from both a frontal and sagittal plane.

Previous research comparing unilateral and bilateral tasks have demonstrated a task-dependent nature of landing from a jump (Dingenen et al., 2015; Earl et al., 2007; Pappas et al., 2007; Taylor et al., 2016). Maturity status has also shown to affect the level of agreement between different rebound jump tests, with less mature cohorts displaying a higher variability in movement patterns (Lloyd et al., 2019), and then, a range of assessments have been suggested when analysing kinematic measures in youth athletes (Read et al., 2019, pp. 336–361). However, the restricted testing time and human resources in applied settings may require coaches to prioritise between screening tools. The knowledge of potential relationships between DVJ and TJA tests, as well as their interaction with maturity status, may assist coaches' decision making to select the most informative jumping and landing assessment in youth soccer. To date, only a recent study (Lloyd et al., 2019) has compared frontal kinematic measures in both tests and across different stages of maturation, showing greater knee medial displacement values for TJA and superior sensitivity to detect differences based on maturation. No previous research (from the authors' knowledge) has provided this information for sagittal plane measures.

Therefore, the purposes of this study were: (1) to determine the inter-rater and intra-rater reliability of frontal and sagittal plane landing kinematic measures during DVJ and TJA tasks in male youth soccer players; (2) to assess the concurrent validity between DVJ and TJA tests for all landing kinematic measures; and (3) to evaluate the ability of both jumping tasks to detect differences between players' stage of maturation. Based on previous research, we hypothesised that: (1) the kinematic measures recorded from both the DVJ (Mizner et al., 2012; Ortiz et al., 2016) and TJA (Lloyd et al., 2019; Read et al., 2018a) would demonstrate high inter- and intra-rater reliability; (2) a weak relationship would be found between DVJ and TJA measures (Dingenen et al., 2015; Earl et al., 2007; Pappas et al., 2007; Taylor et al., 2016); and (3) a greater ability to discriminate among stages of maturation would be shown by the TJA (Lloyd et al., 2019).

2. Methods

2.1. Design

A cross-sectional observational design was used to analyse the reliability, concurrent validity, and maturation-related differences of several frontal and sagittal plane landing kinematic measures during DVJ and TJA among young male soccer players (Fig. 1). This study was conducted during the preseason period (September) of the years 2017 and 2018.

The assessments conducted in each soccer team were divided into 2 different parts within a single testing session. The first part was used to record the anthropometric measures needed to calculate the maturity status. The second part was designed to collect data for the DVJ and TJA tests. A 20-min standardised dynamic warm-up (Taylor et al., 2009) was performed before the DVJ and TJA data collection. All the kinematic variables were retrospectively extracted through 2-D video-analysis.

2.2. Participants

A convenience sample of 223 male youth soccer players from five Spanish soccer clubs completed this study (Table 1). Participants met the following inclusion/exclusion criteria: 1) engaged regularly in soccer training and competitions (at least 2–3 training sessions and 1 match per week), and 2) were free of injuries and delayed onset muscle soreness (DOMS) at the time of testing (self-reported). Participants were asked to refrain from vigorous exercise at least 48 h prior to the testing session. The experimental procedures used in this study were in accordance with the Declaration of Helsinki and were approved by the Ethics and Scientific Committee of the University of Murcia (Spain) (ID: 1551/2017), and written informed consent and assent was obtained from parents and participants.

2.3. Procedures

2.3.1. Anthropometry and maturity status

Body mass in kilograms was measured on a calibrated physician scale (SECA 799, Hamburg, Germany). Standing and sitting heights in centimeters were recorded on a measurement platform (SECA 799, Hamburg, Germany). Players' leg length was calculated as the difference between their recorded standing and sitting heights. Stage of maturation was calculated in a noninvasive manner using the regression equation proposed by Mirwald et al. (2002). This equation has been used to predict maturation status with a standard error of approximately 6 months in paediatric population (Mirwald et al., 2002). To account for the reported error, players were grouped into discrete bands based on their maturational offset (pre-PHV [<−1], circa-PHV [-0.5 to 0.5], post-PHV [>1]), and players with a maturity offset from −1 to −0.5 and 0.5 to 1 were removed from the dataset when players were analysed by stage of maturation (Read et al., 2018a).

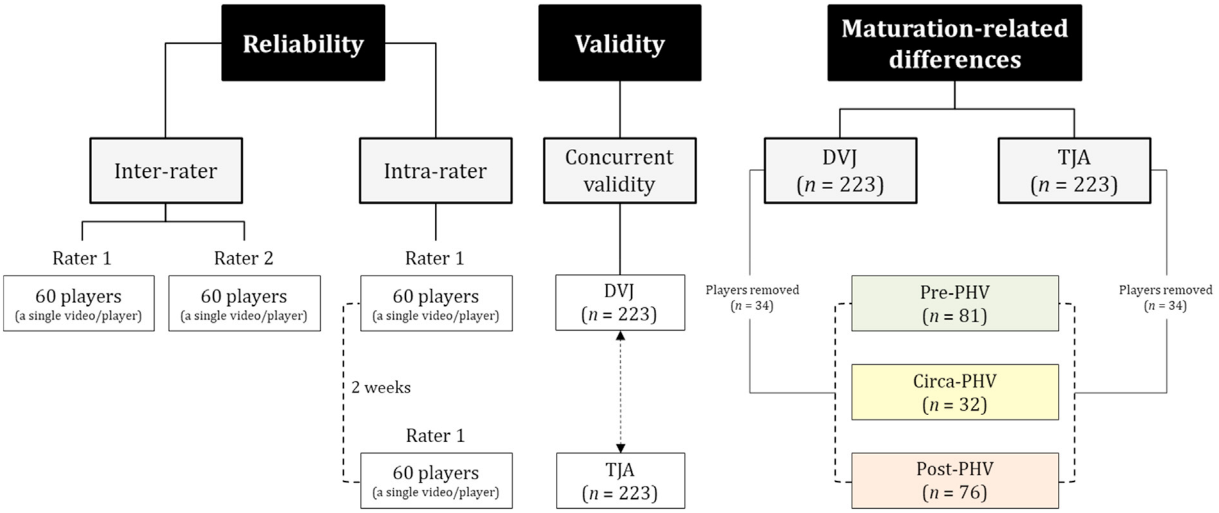

Fig. 1. Study design.

Table 1
Descriptive anthropometric values (mean ± standard deviation) for all the participants and per maturation sub-group.

Group	N	Age (years)	Body mass (kg)	Stature (cm)	Leg length (cm)	Maturity offset
Pre-PHV	81	11.5 ± 1.0	40.7 ± 7.3	149.8 ± 7.3	74.3 ± 4.9	−2.2 ± 0.7
Circa-PHV	32	13.8 ± 0.6	57.1 ± 6.9	167.6 ± 5.2	83.1 ± 5.0	−0.1 ± 0.3
Post-PHV	76	16.7 ± 1.1	67.9 ± 8.6	177.4 ± 6.7	86.6 ± 5.4	2.3 ± 0.8
Whole group	223	14.0 ± 2.4	54.2 ± 13.9	163.9 ± 13.5	80.8 ± 7.3	−0.1 ± 2.0

2.3.2. *Drop vertical jump (DVJ)*

A DVJ without arm swing was performed following the procedures previously described by Onate et al. (2010). Participants stood with feet shoulder-width apart on a 40 cm high box. They were instructed to lean forward and drop from the box. Players were required to land with both feet simultaneously on a contact mat (Ergo Jump Bosco System, Italia) that was located 20 cm in front of the box, then immediately perform a maximal vertical jump minimising ground contact time, and finally land back on the contact mat. After three familiarisation repetitions, each player performed two maximal jumps with at least 1 min of recovery between jumps.

2.3.3. *Tuck jump assessment (TJA)*

Tuck jumps were performed in place for a period of 10 consecutive seconds. Players stood on two vertical strips of tape which were 35 cm apart and connected by a horizontal line forming a H-Shape to ensure correct foot positioning (Lloyd et al., 2019). They were instructed to start with a countermovement and follow with repeated vertical jumps as high as possible while simultaneously pulling their knees up towards their chest (Myer et al., 2008). Players were asked for landing in the same footprint, minimising ground contact time. After three consecutive repetitions to become familiar with the test, a single trial of the TJA was performed by each player.

2.4. *Landing kinematic analysis*

Two-dimensional video cameras (Panasonic Lumix DMC-FZ200, Japan) were positioned in both frontal and sagittal planes at a height of 0.70 m and a distance of 5 m from the landing area to capture the tests and, retrospectively, players' landing technique was assessed through a free available software (Kinovea 0.8.15, USA). For each video, knee displacement (valgus vs. varus alignment) in the frontal plane, and hip, knee and ankle flexion angles at initial contact and peak flexion in the sagittal plane were calculated. All kinematic data were recorded at 100 fps using a high-definition resolution.

Some previous studies (Dingenen et al., 2015; Howe et al., 2019; Ortiz et al., 2016), but not all (Calo et al., 2019; King & Belyea, 2015; Mizner et al., 2012), have used reflective markers on bony landmarks (including joints centres) to guide the calculation of the 2D kinematic measures. However, a pilot study carried out in our laboratory with five physically active young adults (Sport Sciences undergraduate students) and one tester with more than 5 years of experience in kinematic assessments demonstrated very high correlation scores (ICC > 0.9) for the 2D measures of frontal plane knee alignment and sagittal plane hip and knee motions obtained during drop vertical landings and with and without the use of reflective markers on bony landmarks to guide their calculation. In addition, markers can often slide on the skin during the execution of high intensity weight-bearing dynamic tasks and this may lead to an increased measurement error. Consequently, and with the aim of making the data reduction process more time-efficient and generalisable for applied settings, no markers were used for the landing kinematic analysis in this research.

Knee displacement was assessed for both the dominant (i.e., players' preferred kicking leg) and non-dominant legs by measuring the frontal plane projection angle (FPPA) at the point of peak maximum knee flexion (Mizner et al., 2012; Ortiz et al., 2016; Read et al., 2018a). FPPA was measured as the angle formed by the intersection of two lines: a straight line that bisected the thigh outline, terminating at the rater's estimation of the bisection of the femoral epicondyles, and a straight line that bisected the borders of the lower leg, terminating at the estimated position of the ankle's lateral malleolus (Calo et al., 2019; Mizner et al., 2012). Similar to Mizner et al. (2012), the epicondyle estimation was made from available visual landmarks such as the outline of shadowing of the patella, muscular shape outline of the quadriceps and the thickness of the leg's outline in the area of the knee joint. The ankle malleolus position was made from available visual landmarks such as shoe position, bony outlines or shadows of the bones of the leg and the thickness of the leg outline in the area of the ankle joint. Peak knee flexion was defined as the one frame before the subject started to increase knee extension in order to perform the maximum vertical jump (Mizner et al., 2012; Ortiz et al., 2016; Read et al., 2018a). FPPA was calculated for each DVJ and each ground contact during the TJA. The mean FPPA values for the DVJ trials, and the mean of the two maximum valgus scores for the TJA were used for the analysis. Values > 0 were indicative of knee valgus, whereas values < 0 denoted knee varus.

Hip (HF), knee (KF) and ankle (AF) flexion angles at initial contact (IC) and peak flexion (PF) were assessed for the dominant leg, based on the methodology described in previous studies (Calo et al., 2019; Dingenen et al., 2015; King & Belyea, 2015). HF, KF and AF angles were measured as the angles formed by straight lines joining the estimated hip rotation axis with the projection of the spine in neutral position and the lateral femoral epicondyle (HF), the lateral femoral epicondyle with the estimated hip rotation axis and the lateral malleolus (KF), and the lateral malleolus with the lateral femoral epicondyle and the tip of the foot (AF) (Calo et al., 2019; King & Belyea, 2015). IC was determined as the first video frame in which ground contact was observed, and PF was defined as the deepest landing position (i.e., where no movement occurred at the hip, knee and ankle) (Dingenen et al., 2015). All the sagittal variables were measured for each DVJ and each ground contact during the TJA. The mean values for the DVJ trials, and the mean values of the two worst (maximum valgus) repetitions for the TJA were used for the subsequent analysis. Lower HF and KF angles were indicative of decreased flexion (stiffer landing pattern), whereas greater angles represented increased flexion during landing. A positive value in AF corresponds to a dorsiflexed ankle while a negative value represents a plantar flexed ankle (Fig. 2).

2.5. Statistical analysis

The distribution of raw data sets was checked using the Kolmogorov-Smirnov test and demonstrated that all data had a normal distribution ($p > 0.05$). Descriptive statistics including means and standard deviations (SDs) were calculated for all measures.

2.5.1. Reliability

The inter- and intra-rater reliability for frontal and sagittal measures were assessed on a randomly selected sub-section ($n = 60$) of the sample included in the current study. Two sport scientists (FJR-P and IR-P) with more than 5 years of experience in landing kinematic analysis evaluated 60 videos in a randomised order to determine the inter-rater reliability. For intra-rater reliability, a single rater (FJR-P) assessed the same 60 videos on two occasions separated by a two-week interval to determine the repeatability of the measure.

A two-way random intra-class correlation coefficient ($ICC_{2,1}$) with absolute agreement was used to analyse both inter- and intra-rater reliability. Magnitudes of ICC were classified according to the following thresholds: <0.5, poor; 0.5 to 0.74, moderate; 0.75 to 0.9, good; and >0.9, excellent reliability (Portney, 2020). The precision of measurement was also determined using the standardised typical error of measurement (TEM_{ST}), the typical percentage error (coefficient of variation [CV_{TE}]) and the minimal detectable change at a 95% (MDC_{95}) confidence interval (CI) using the Hopkins' spreadsheet (Hopkins, 2015). As previously suggested (Smith & Hopkins, 2011), half of the thresholds of the modified Cohen scale and the arbitrary value (10%) proposed by Weir and Vincent (2020) were used to interpret the TEM_{ST} and the CV_{TE}, respectively. Thus, the TEM_{ST} was interpreted using the following scale: <0.1, trivial; 0.1–0.3, small; 0.3–0.6, moderate; 0.6–1.0, large; 1.0–2.0, very large; >2.0, extremely large (Hopkins, 2015). A value $\leq$ 5% was used to interpret the CV_{TE}.

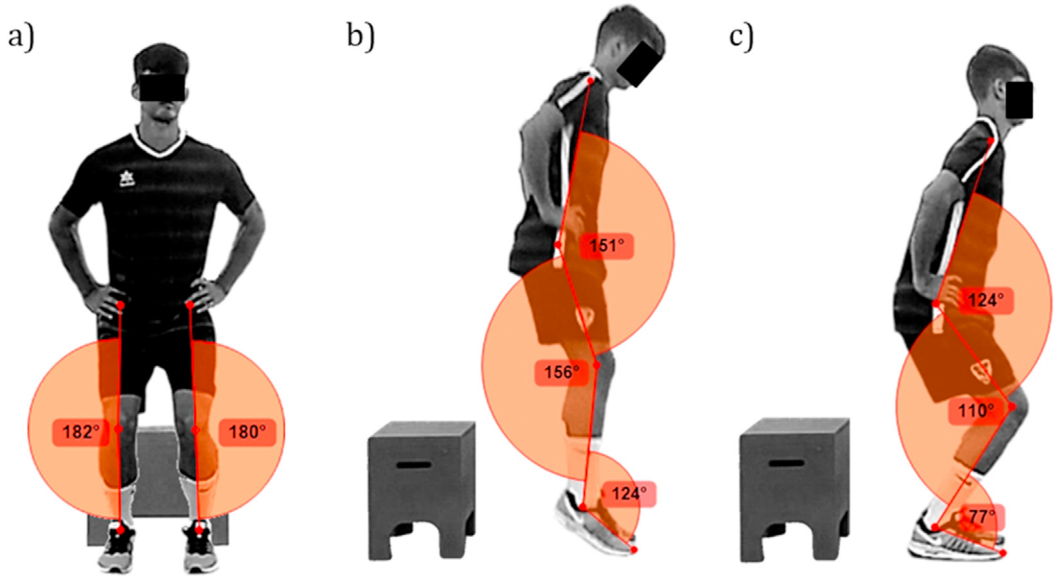

Fig. 2. Frontal (a) and sagittal (b [initial contact] and c [peak flexion]) plane landing kinematic measures. Note: for the drawn angles presented in the image a), 180 represents a neutral alignment (0) and values < 180 and > 180 are indicative of knee valgus and varus, respectively. For the HF and KF drawn angles displayed in the images b) and c), 180 represents the standard anatomical position while 90 is the reference for the AF in these pictures. Thus, the final angle values are reported as 180 minus the drawn angle for all kinematic measures (e.g., a drawn angle of 151 [image b] is reported as 29 of HF-IC), with the exception of AF where 90 minus the drawn angle value is used (e.g., a drawn angle of 77 [image c] is reported as 13 of AF-PF [dorsiflexion]).

2.5.2. Concurrent validity

To compare values obtained from the TJA with those from the DVJ, the Pearson's product-moment correlation coefficient with a 95% CI and the standardised typical error of estimate (TEE_{ST}) were calculated. Magnitudes of Pearson (*r*) correlation coefficients were assessed using the following scale: <0.80 low, 0.80–0.90 moderate, and >0.90 high (Hopkins, 2000), while the TEE_{ST} was interpreted using the same scale as the TEM_{ST}.

To examine possible differences between DVJ and TJA mean values for each kinematic measure, a Bayesian paired samples *t*-test was also used. In these comparisons, the quantification of the relative degree of evidence for supporting the null hypothesis (H_0 = no significant differences between tests) or alternative hypothesis (H_1 = significant differences between tests) was performed through the Bayesian factor (BF_{10}) (Rouder et al., 2012). The BF_{10} was interpreted using the evidence categories suggested by Lee and Wagenmakers (2013): <1/100 = extreme evidence for H_0, from 1/100 to 1/30 = very strong evidence for H_0, from 1/30 to 1/10 = strong evidence for H_0, from 1/10 to 1/3 = moderate evidence for H_0, from 1/3 to 1 anecdotal evidence for H_0, from 1 to 3 = anecdotal evidence for H_1, from 3 to 10 = moderate evidence for H_1, from 10 to 30 = strong evidence for H_1, from 30 to 100 = very strong evidence for H_1, >100 extreme evidence for H_1. The median and the 95% central credible interval of the posterior distribution of the standardised effect size (δ) (i.e., the population version of Cohen's *d*) were also calculated for each of the paired-comparisons carried out. Magnitudes of the posterior distribution of the standardised effect size were classified as: trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0) and very large (2.0–4.0) (Batterham & Hopkins, 2006). Only those comparisons that showed at least a strong evidence for supporting the H_1 ($BF_{10} > 10$), an error percentage < 10 (which indicates great stability of the numerical algorithm that was used to obtain the result) and $\delta > 0.6$ (at least moderate) were considered robust to describe significant differences.

2.5.3. Maturation-related differences

A Bayesian analysis of variance (ANOVA) was conducted to examine whether there were significant differences among stages of maturation (pre-PHV vs. circa-PHV vs. post-PHV) for each frontal and sagittal plane measure in DVJ and TJA tests. In the post hoc analysis, posterior odds were corrected for multiple testing by fixing to 0.5 the prior probability that the null hypothesis holds across all comparisons (Westfall et al., 1997). In these comparisons, the quantification of the relative degree of evidence for supporting the H_0 (no significant differences between maturation groups) or H_1 (significant differences between maturation groups) was performed through the BF_{10} (Rouder et al., 2012). The BF_{10} was interpreted using the evidence categories suggested (Lee & Wagenmakers, 2013) as before. Likewise, only those comparisons that reported strong evidence ($BF_{10} > 10$; error < 10; $\delta > 0.6$) for supporting H_1 were considered robust to describe significant differences between maturation groups.

All statistical analyses were performed using the JASP computer software (version 0.13.1), the Statistical Package for Social Science (IBM Corp.; IBM SPSS Statistics for Windows, version 20.0, Armonk, NY, USA), and an online spreadsheet (www.sportsci.org).

3. Results

3.1. Reliability

Table 2 shows inter-rater reliability data for all frontal and sagittal plane variables in DVJ and TJA tests. Most of the measures selected to assess the landing kinematic pattern within this study evidenced good-to-excellent reliability when analysed by two different testers (ICC = 0.87–0.97; TEM_{ST} = 0.2–0.3; CV_{TE} = 1.0–2.5), except for the AF which showed weaker reliability values with moderate (AF-IC in both DVJ and TJA, and AF-PF in TJA) to poor (AF-PF in DVJ) ICCs and moderate TEM_{ST}. The MDC_{95} scores ranged from 5 to 12 for all kinematic variables in both jumping tasks.

All the frontal and sagittal plane measures demonstrated good-to-excellent intra-rater reliability (ICC = 0.79–0.99; CV_{TE} = 0.6–2.7) (Table 3). Regarding the MDC_{95}, scores ranged from 3.8 to 5.7 and from 2.9 to 8.7 for all DVJ and TJA kinematic variables, respectively. Although adequate ICC and CV_{TE} values were found for the AF-IC and AF-PF measures, these angles presented again slightly greater TEM_{ST} (AF-IC = 0.4 for TJA; AF-PF ~ 0.4 for DVJ and TJA) compared to the rest of variables.

3.2. Concurrent validity

Table 4 displays concurrent validity between the DVJ and TJA tests. Results revealed poor validity scores, showing low correlation (all *r* values < 0.56) and very-to-extremely large TEE_{ST} (all TEE_{ST} values > 1.49) between both jumping tasks for all frontal and sagittal variables measured and maturation groups.

The Bayesian *t*-test reported strong evidence ($BF_{10} > 10$; error < 10; $\delta > 0.6$) for supporting the H_1 (differences between DVJ and TJA) for FPPA (dominant and non-dominant) and KF-IC, KF-PF and HF-PF values in the whole group. When categorising by stage of maturation, these significant differences were maintained for FPPA, HF-PF and KF-PF across all groups.

3.3. Maturation-related differences

The Bayesian ANOVA did not show strong evidence ($BF_{10} > 10$; error < 10; $\delta > 0.6$) for supporting the H_1 (differences between stages of maturation) for any frontal and sagittal measure of the DVJ (Fig. 3). By contrast, strong evidence for supporting H_1 in the TJA was found. Pairwise comparisons showed significant higher knee valgus in dominant and non-dominant legs ($BF_{10} > 100$ [extreme]; error < 0.001; δ = 0.6–0.8), and greater HF (at IC and PF), greater KF-IC, and lower AF-IC (plantar flexion) in the sagittal plane for pre-PHV compared to post-PHV group ($BF_{10} > 30$ [very strong]; error < 0.001; δ = 0.6–1.2). Pre-PHV group also displayed greater HF-IC and KF-IC than circa-PHV group ($BF_{10} > 30$ [very strong]; error < 0.001; δ = 0.6–0.9) (Fig. 4).

4. Discussion

The main findings of this study revealed that the 2D landing video analysis was a reliable tool for assessing the knee FPPA as well as the HF and KF angles during DVJ and TJA tasks by experienced single or different testers. Although both tests have been used to examine landing technique previously, the results of this research showed a low relationship between DVJ and TJA kinematic measures, demonstrating significant higher FPPA and lower HF-PF and KF-PF values during the TJA test. Furthermore, while the DVJ was not able to report strong evidence for supporting between group differences regarding the maturity status, the TJA displayed a higher ability to discriminate between developmental stages for all frontal and sagittal measures.

4.1. Reliability

Our first hypothesis, that kinematic assessments of DVJ and TJA would have a better inter- and intra-rater reliability, was mostly supported since good-to-excellent reliability values were found for

Table 2
Inter-rater reliability for frontal and sagittal plane measures.

Measurement	Rater 1	Rater 2	ChM	TEM$_{ST}$	CV$_{TE}$	MDC$_{95}$	ICC$_{2,1}$ (95% CI)
	Mean ± SD	Mean ± SD	Mean ± SD				
			DVJ				
FPPA-D	0.8 ± 9.9	−1.6 ± 10.7	−2.3 ± 3.6	0.25	1.41	7.10	0.92 (0.77–0.96)
FPPA-ND	−3.7 ± 12.5	−4.4 ± 13.2	−0.7 ± 3.4	0.19	1.34	6.65	0.96 (0.94–0.98)
HF-IC	40.2 ± 9.5	39.1 ± 10.0	−1.2 ± 3.7	0.27	1.95	7.32	0.92 (0.87–0.95)
KF-IC	32.3 ± 6.4	32.8 ± 6.0	0.5 ± 3.2	0.36	1.55	6.26	0.87 (0.79–0.92)
AF-IC	−26.7 ± 11.0	−34.7 ± 13.8	−7.9 ± 6.0	0.34	3.74	11.81	0.74 (0.00–0.91)
HF-PF	69.1 ± 17.0	68.4 ± 17.3	−0.7 ± 3.9	0.16	2.50	7.65	0.97 (0.96–0.98)
KF-PF	81.2 ± 9.3	79.3 ± 8.0	−1.9 ± 3.0	0.24	2.25	5.88	0.92 (0.78–0.96)
AF-PF	12.4 ± 4.8	5.0 ± 4.9	−7.3 ± 3.9	0.57	3.54	7.68	0.32 (−0.09 − 0.67)
			TJA				
FPPA-D	0.9 ± 10.4	1.1 ± 11.5	0.2 ± 2.9	0.19	1.18	5.65	0.97 (0.94–0.98)
FPPA-ND	−1.1 ± 10.3	0.2 ± 10.9	1.4 ± 2.6	0.17	1.02	5.04	0.96 (0.91–0.98)
HF-IC	32.6 ± 11.8	33.2 ± 12.3	0.7 ± 4.8	0.28	2.38	9.37	0.92 (0.87–0.95)
KF-IC	35.1 ± 8.1	36.0 ± 7.7	0.9 ± 3.1	0.28	1.56	6.13	0.92 (0.86–0.95)
AF-IC	−30.4 ± 7.6	−33.5 ± 7.5	−3.1 ± 6.1	0.57	3.62	11.97	0.62 (0.38–0.78)
HF-PF	37.5 ± 12.9	39.0 ± 12.8	1.5 ± 3.7	0.21	1.87	7.35	0.95 (0.91–0.97)
KF-PF	59.8 ± 11.0	60.2 ± 10.8	0.5 ± 3.0	0.20	1.79	5.90	0.96 (0.94–0.98)
AF-PF	10.7 ± 5.1	9.8 ± 5.4	−0.9 ± 3.9	0.53	3.56	7.73	0.71 (0.56–0.82)

ChM: change in the mean; TEM$_{ST}$: standardised typical error of measurement; CV$_{TE}$: coefficient of variation expressed as percentage values; MDC$_{95}$: minimal detectable change 95%; ICC: intraclass correlation coefficients; CI: confidence interval; DVJ: drop vertical jump; TJA: tuck jump assessment; FPPA: frontal plane projection angle; HF: hip flexion; KF: knee flexion; AF: ankle flexion; D: dominant leg; ND: non-dominant leg; IC: initial contact; PF: peak flexion.

Table 3
Intra-rater reliability for frontal and sagittal plane measures.

Measurement	Assessment 1	Assessment 2	ChM	TEM$_{ST}$	CV$_{TE}$	MDC$_{95}$	ICC$_{2,1}$ (95% CI)
	Mean ± SD	Mean ± SD	Mean ± SD				
			DVJ				
FPPA-D	0.8 ± 9.9	−0.5 ± 10.1	−1.3 ± 1.9	0.14	0.76	3.77	0.97 (0.92–0.99)
FPPA-ND	−3.7 ± 12.5	−5.1 ± 12.8	−1.4 ± 2.1	0.12	0.80	4.16	0.98 (0.94–0.99)
HF-IC	40.2 ± 9.5	38.8 ± 10.0	−1.5 ± 2.6	0.19	1.35	5.18	0.95 (0.89–0.98)
KF-IC	32.3 ± 6.4	30.9 ± 6.5	−1.4 ± 2.6	0.28	1.25	5.07	0.90 (0.77–0.95)
AF-IC	−26.7 ± 11.0	−27.5 ± 11.0	−0.8 ± 3.4	0.22	2.18	6.74	0.95 (0.92–0.97)
HF-PF	69.1 ± 17.0	68.3 ± 17.4	−0.8 ± 2.6	0.11	1.67	5.16	0.99 (0.98–0.99)
KF-PF	81.2 ± 9.3	79.5 ± 8.9	−1.7 ± 2.2	0.17	1.64	4.38	0.95 (0.83–0.98)
AF-PF	12.4 ± 4.8	11.9 ± 4.0	−0.4 ± 2.9	0.46	2.70	5.68	0.79 (0.67–0.87)
			TJA				
FPPA-D	0.9 ± 10.4	0.8 ± 10.7	−0.1 ± 1.6	0.11	0.66	3.24	0.99 (0.98–0.99)
FPPA-ND	−1.1 ± 10.3	−1.3 ± 10.3	−0.1 ± 1.5	0.10	0.58	2.91	0.99 (0.98–0.99)
HF-IC	32.6 ± 11.8	31.4 ± 11.8	−1.2 ± 2.1	0.12	0.99	4.05	0.98 (0.95–0.99)
KF-IC	35.1 ± 8.1	35.0 ± 7.7	−0.1 ± 1.8	0.16	0.89	3.52	0.97 (0.96–0.99)
AF-IC	−30.4 ± 7.6	−29.8 ± 7.9	0.6 ± 4.4	0.41	2.74	8.70	0.83 (0.74–0.90)
HF-PF	37.5 ± 12.9	36.1 ± 13.4	−1.4 ± 2.2	0.12	1.11	4.27	0.98 (0.94–0.99)
KF-PF	59.8 ± 11.0	59.4 ± 11.4	−0.4 ± 1.7	0.11	1.07	3.38	0.99 (0.98–0.99)
AF-PF	10.7 ± 5.1	11.1 ± 5.6	0.4 ± 2.8	0.37	2.52	5.49	0.87 (0.78–0.92)

ChM: change in the mean; TEM$_{ST}$: standardised typical error of measurement; CV$_{TE}$: coefficient of variation expressed as percentage values; MDC$_{95}$: minimal detectable change 95%; ICC: intraclass correlation coefficients; CI: confidence interval; DVJ: drop vertical jump; TJA: tuck jump assessment; FPPA: frontal plane projection angle; HF: hip flexion; KF: knee flexion; AF: ankle flexion; D: dominant leg; ND: non-dominant leg; IC: initial contact; PF: peak flexion.

all the variables, with the only exception of the inter-rater AF measures. These results are in agreement with previous studies examining intra- and inter-rater reliability for frontal (Mizner et al., 2012) and sagittal (Dingenen et al., 2015) kinematic measures during DVJs in adult athletes, which have shown excellent values for FPPA, HF-PF, KF-PF and AF-PF (ICCs $\geq$ 0.9), and also with the very large intra-rater ICCs ($\geq$ 0.9) recently reported for FPPA during TJA tasks in youth soccer players (Lloyd et al., 2019; Read et al., 2018a). The reduced reliability reported for the AF-IC and AF-PF variables may be partly explained by the smaller between-player variation presented for these values, together with the increased complexity of drawing accurate angles overlapping the players' footwear. In fact, intra-rater assessments also showed slightly poorer ICCs, CV$_{TE}$, and TEM$_{ST}$ scores as well as greater MDC$_{95}$ values (ranged from 5.5 to 8.7) for both AF angles. In other variables, changes larger than 3 for FPPA and 3-5 for sagittal measures would be needed to ensure that changes in kinematics are not simply caused by measurement errors when assessed by the same rater. These values approximately double if the assessments are conducted by two different raters (5-7 for FPPA and 6-9 for HF and KF angles). Nevertheless, to accept a meaningful change when implementing an intervention, further errors should also be taken into consideration such as inter-trial and inter-session players' variability (Malfait et al., 2014). To the authors' knowledge, there is no previous research examining inter-trial and inter-session reliability for 2D video analysis during DVJ and TJA landings in youth soccer players.

4.2. Concurrent validity

Landing technique seems to be task-dependent. Several studies have found different landing kinematic patterns for unilateral and

Table 4
Validity for the DVJ vs. TJA frontal and sagittal plane measures.

Measurement	DVJ	TJA	TEE$_{ST}$	Pearson r (95% CI)
	Mean ± SD	Mean ± SD		
Whole group				
FPPA-D	−0.9 ± 10.1	9.7 ± 8.7*	1.99	0.45 (0.36–0.53)
FPPA-ND	−2.8 ± 10.5	9.1 ± 8.1*	1.82	0.48 (0.39–0.56)
HF-IC	38.2 ± 9.6	34.4 ± 13.7	13.27	−0.08 (−0.19 − 0.04)
KF-IC	30.1 ± 8.4	38.9 ± 7.5*	9.37	−0.11 (−0.22 − 0.01)
AF-IC	−30.3 ± 10.9	−28.0 ± 8.3	41.59	0.02 (−0.09 − 0.14)
HF-PF	64.4 ± 16.1	34.4 ± 11.7*	4.66	0.21 (0.10–0.31)
KF-PF	77.5 ± 10.2	56.1 ± 9.7*	4.47	0.22 (0.11–0.32)
AF-PF	10.9 ± 6.2	10.5 ± 5.7	4.96	0.20 (0.09–0.30)
Pre-PHV				
FPPA-D	0.3 ± 10.2	12.2 ± 8.3*	2.38	0.39 (0.22–0.53)
FPPA-ND	0.3 ± 9.6	12.7 ± 7.5*	2.41	0.38 (0.21–0.53)
HF-IC	37.4 ± 8.8	42.6 ± 13.2	31.00	0.03 (−0.15 − 0.22)
KF-IC	27.9 ± 7.0	42.2 ± 7.3*	17.61	0.06 (−0.13 − 0.24)
AF-IC	−30.5 ± 11.6	−25.9 ± 8.6	18.96	−0.05 (−0.24 − 0.13)
HF-PF	64.9 ± 15.6	38.9 ± 12.9*	4.67	0.21 (0.03–0.38)
KF-PF	77.7 ± 10.4	57.5 ± 10.3*	3.18	0.30 (0.12–0.46)
AF-PF	12.1 ± 6.3	11.1 ± 6.1	2.95	0.32 (0.14–0.48)
Circa-PHV				
FPPA-D	2.9 ± 9.0	11.3 ± 5.9*	1.73	0.50 (0.24–0.69)
FPPA-ND	−2.2 ± 10.2	9.2 ± 7.2*	2.11	0.43 (0.15–0.64)
HF-IC	36.7 ± 9.9	29.9 ± 12.4	10.76	0.09 (−0.21 − 0.38)
KF-IC	31.0 ± 8.8	36.6 ± 8.2	22.67	0.04 (−0.26 − 0.34)
AF-IC	−32.6 ± 9.6	−26.3 ± 7.5	3.59	0.27 (−0.04 − 0.53)
HF-PF	62.9 ± 15.9	33.4 ± 9.3*	8.06	0.12 (−0.18 − 0.41)
KF-PF	75.9 ± 10.1	57.0 ± 8.5*	8.96	0.11 (−0.20 − 0.40)
AF-PF	9.3 ± 6.0	11.1 ± 5.9	4.60	0.21 (−0.09 − 0.48)
Post-PHV				
FPPA-D	−3.0 ± 10.3	6.9 ± 8.9*	1.66	0.52 (0.36–0.64)
FPPA-ND	−5.8 ± 11.6	6.0 ± 8.0*	1.49	0.56 (0.41–0.68)
HF-IC	39.3 ± 10.1	27.1 ± 10.4*	6.92	−0.14 (−0.33 − 0.05)
KF-IC	32.3 ± 9.1	36.6 ± 6.3	6.72	−0.15 (−0.33 − 0.05)
AF-IC	−29.2 ± 11.0	−30.6 ± 8.1	17.38	0.06 (−0.14 − 0.25)
HF-PF	63.5 ± 15.8	29.4 ± 8.9*	4.16	0.23 (0.04–0.41)
KF-PF	77.6 ± 9.8	54.0 ± 9.3*	4.43	0.22 (0.03–0.39)
AF-PF	10.7 ± 6.1	9.9 ± 5.1	5.74	0.17 (−0.02 − 0.35)

* Significant differences compared to the DVJ values ($BF_{10} > 10$; error < 10; $\delta > 0.6$). DVJ: drop vertical jump; TJA: tuck jump assessment; TEE$_{ST}$; typical error of estimate; CI: confidence interval; FPPA: frontal plane projection angle; HF: hip flexion; KF: knee flexion; AF: ankle flexion; D: dominant leg; ND: non-dominant leg; IC: initial contact; PF: peak flexion.

bilateral dynamic actions (Dingenen et al., 2015; Earl et al., 2007; Pappas et al., 2007), and also when landing from a different jumping task (Heebner et al., 2017). In this sense, the results of the present study also support our second hypothesis: the DVJ and TJA tests showed highly different landing techniques. Pairwise comparisons between landing tasks displayed greater valgus alignments (FPPA) in the frontal plane and reduced flexion patterns (HF-PF and KF-PF) in the sagittal plane for the TJA in the whole group and across all stages of maturation when compared to the DVJ. Furthermore, these findings are in line with the recent data reported by Lloyd et al. (2019) in the only previous study that has compared both DVJ and TJA tasks. In that research (Lloyd et al., 2019), the TJA was also more likely to expose male youth soccer players to greater FPPA values in both legs. To a certain extent, these results may be explicated by the different nature of both landing performances. When landing from a standardised height like in the DVJ, impact forces are controlled by muscles that go from rest to eccentric contraction (Read et al., 2016b). This situation may artificially promote an anticipated muscle response (feedforward control mechanisms) (Lloyd et al., 2019; Read et al., 2016b; Russell et al., 2007) to help lower extremity stabilisation during landing. However, in a more functional landing task such as the TJA, individuals must control the landing with musculature just activated to move the body during the propulsion phase (Read et al., 2016b; Russell et al., 2007). Thus, coordination deficits in musculature contractions may compromise the ability of the neuromuscular system to prepare the landing phase in this scenario (Myer et al., 2004; Russell et al., 2007). Additionally, and despite the fact both are rebounding tests, the TJA requires repetitively performance of what may be more demanding jumps (knee to chest) during 10 s (Myer et al., 2008). Accumulated fatigue in later repetitions may result in greater variability between jumps and the appearance of kinematic flaws compared to a single DVJ.

Studies on knee biomechanics have indicated that valgus collapse is often coupled with decreased KF and HF (Brophy et al., 2010). Dynamic knee valgus overloads the MCL and ACL, increasing the injury risk (Hewett et al., 2004; Yu & Garrett, 2007). At low KF angles, quadriceps contractions pull the tibia forward and also increase the stress on the ACL (Myer et al., 2004). Therefore, aberrant movements (i.e., higher FPPA values and reduced HF-PF and KF-PF) that contribute to sports injury might be better detected by the TJA rather than the DVJ when screening young athletes. The development of neuromuscular control training programs in players showing greater valgus scores and/or stiffer landing techniques may help to prevent an excessive loading on knee ligaments that place the athlete at risk of sustaining an injury (De Ste Croix et al., 2018; Myer et al., 2009). To optimise their effects on joint kinematics, neuromuscular programs should incorporate a combination of trunk and lower extremity strength, dynamic balance and plyometric exercises (Sugimoto et al., 2016), with coaches providing appropriate visual and verbal cues to ensure the correct joint alignment during exercise executions (Ling et al., 2021; Sugimoto et al., 2016).

4.3. Maturation-related differences

Our third hypothesis, that a greater ability to discriminate between developmental stages would be revealed by the TJA, was also confirmed. Although a trend towards the reduction of FPPA values with advancing maturity was observed for both DVJ and TJA tasks, the magnitude of evidence for supporting these findings was only meaningful for paired comparisons between pre- and post-PHV groups in the TJA. These results are consistent with those obtained in previous research (Lloyd et al., 2019; Read et al., 2018a), which indicate that reductions in valgus could be due to the benefits of growth and maturation in terms of increased muscular strength and motor control (Croce et al., 2004; Jones et al., 2000; Russell et al., 2007). Older athletes have shown higher pre-landing co-contractions (hamstring pre-activation) than children, suggesting feedforward mechanisms develop with maturation and subsequent joint stabilisation (Croce et al., 2004; Russell et al., 2007). Similarly, the higher jump heights presented by more mature players may reveal a better jumping ability that assists landing skills providing more time to prepare for landing (Russell et al., 2007). In this regard, a relationship between knee valgus displacements during the TJA and heightened injury risk has been identified for U12 male soccer players (Read et al., 2018b). Consequently, the assessment of dynamic knee valgus during TJA has been suggested as a worthwhile screen especially for prepubescent athletes (Read et al., 2018b).

The data obtained in this study also reflects different strategies to control the impact force of TJA landings in the sagittal plane across maturation groups. Players classified in the pre-PHV group exhibited increased HF and KF angles (especially at IC) in comparison with players at circa- and post-PHV groups. These results suggest that, despite their higher knee valgus scores, prepubescent soccer players rely on HF and KF movements as strategy for modulating the external ground reaction forces produced by

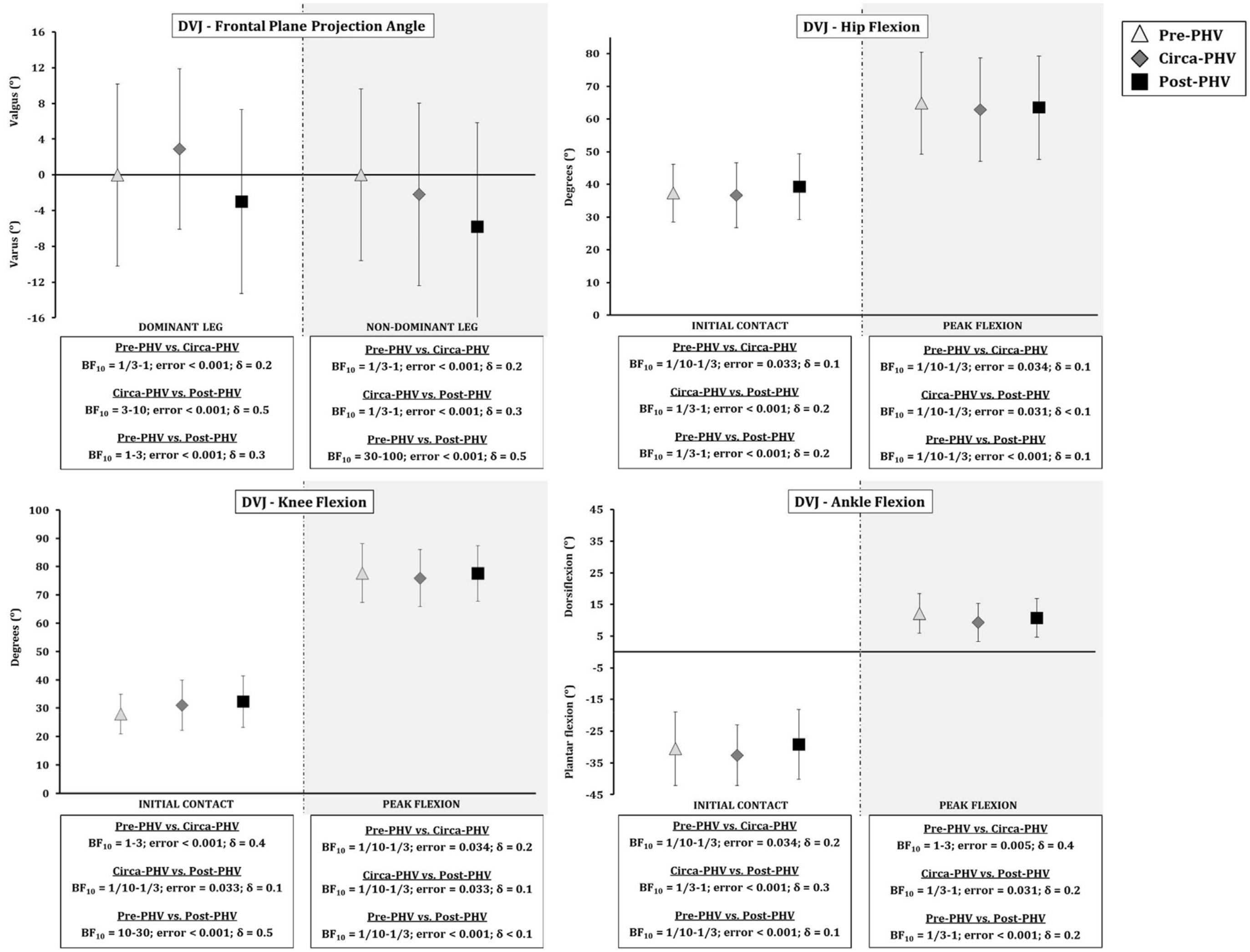

Fig. 3. Maturation-related differences for all frontal and sagittal plane measures in the DVJ test. *: $BF_{10} > 10$; error < 10; $\delta > 0.6$.

landing actions more than their pubescent and postpubescent peers. This seems not to be in agreement with previous findings in young females where decreased hip and knee flexion has been associated with greater knee valgus, suggesting the coupling of frontal and sagittal motions leads female athletes to their higher risk of knee injury (Pollard et al., 2010). In this sense, the increased HF and KF shown by players at pre-PHV in our study might help to lessen the negative effects of their increased knee valgus profile. While the reasons for this increased flexion pattern in the pre-PHV group are not known, the potential differences in timing of strength and neuromuscular control development between the proximal and distal body segments might contribute to some degree to the application of a more proximal control strategy (focused on large muscles in the trunk and hip) at earlier maturational stages, as hypothesised in previous research (Lehnert et al., 2019; Russell et al., 2007). The significant reductions on HF and KF angles in conjunction with the exponential increment in body weight throughout stages of maturation could also be behind the linear increment shown in ACL injury rates after 12 years of age (Leppänen et al., 2017; Takahashi & Okuwaki, 2017; Yu et al., 2005). Thus, the detection of stiffer landing patterns might be even more relevant than knee frontal plane mechanics for reducing the injury risk in circa- and post-PHV groups. Similarly, although the increased ankle plantar flexion at IC shown by players in the post-PHV group could also support this progression towards distal control strategies (based on ankle motions first) as growth and maturation advance, the low reliability values reported for ankle measures in the current study recommend caution with these findings.

4.4. Strengths and limitations

Reliability of quantitative kinematic measurements during the TJA has been limited to intra-rater assessments of knee valgus (using ICC (Lloyd et al., 2019) and Cohen's Kappa (Read et al., 2018a)). This study helps then to fill knowledge gaps, providing a comprehensive analysis (including additional statistics for precision of measurements) of inter- and intra-rater reliability beyond just the knee from a frontal plane in both the TJA and DVJ. Furthermore, meaningful kinematic differences between these tasks are reported and should be taken into account when assessing landing technique in youth athletes. Despite these contributions to the available literature, the current study also has some limitations that should be mentioned. Kinematic data was measured through 2D video recordings instead of 3D motion analysis systems, which have been considered the gold standard measurement (Dingenen et al., 2015; McLean et al., 2005). This limited the examination of landing technique to the frontal and sagittal planes, preventing the

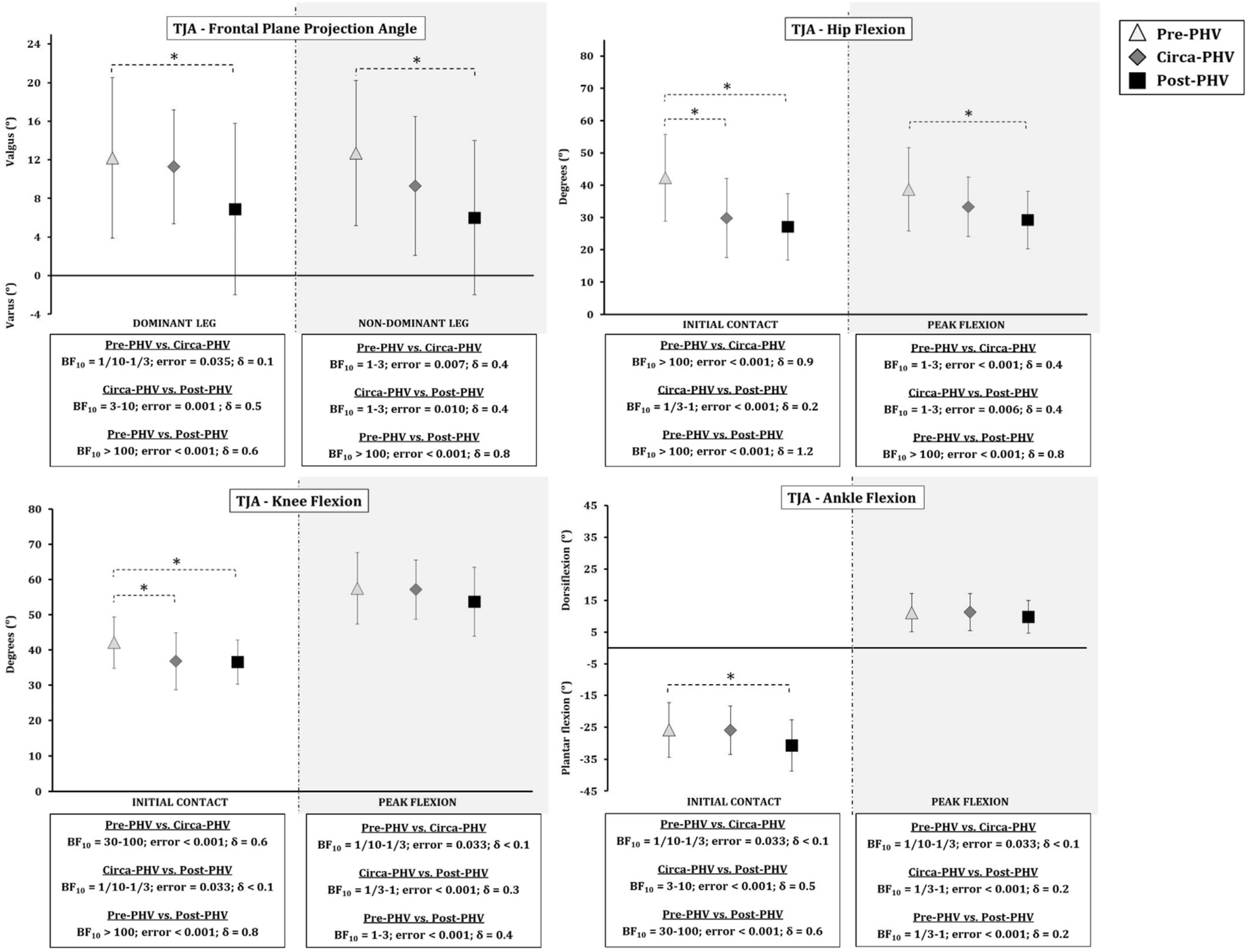

Fig. 4. Maturation-related differences for all frontal and sagittal plane measures in the TJA test. *: $BF_{10} > 10$; error < 10; $\delta > 0.6$.

analysis of movements in the transverse plane. However, 2D video analysis has previously shown to be a valid, less expensive and time demanding alternative to 3D motion caption systems (Lu et al., 2020) and thus, a more accessible tool to screen athletes in the real framework of youth sports. Additionally, while both dominant and non-dominant legs were analysed for FPPA, sagittal measures were only calculated in players' dominant leg for operational reasons. Nevertheless, minimal (non-clinically relevant) differences in sagittal plane landing pattern between both legs have been found for bilateral DVJs (McPherson et al., 2016), so the trends shown in this study for HF, KF and AF measures can be expected to be similar for the non-dominant leg. Finally, although the purpose of the paper was to compare movement patterns in the TJA and DVJ using the procedures most typically used by clinicians and researchers, it should be noted that the slightly different approaches to assessing each task might impact the values reported for each test.

5. Conclusion

Both the DVJ and TJA tests are reliable tools to assess frontal and sagittal plane lower-extremity landing kinematics in youth soccer players. However, outcomes from the two tests are not well related. The TJA may be viewed as a more informative tool for landing technique assessments given it shows greater levels of FPPA and can also detect differences between players of different maturity. Due to the deficits demonstrated in the frontal plane by players' at pre-PHV group and in the sagittal plane by players' at circa- and post-PHV groups, the implementation of neuromuscular strategies aimed to improve muscular strength, dynamic balance and plyometric skills is recommended from pre-puberty and across all periods of growth and maturation to mitigate the risk of injury in youth soccer.

Ethical approval

The experimental procedures used in this study were in accordance with the Declaration of Helsinki and were approved by the Ethics and Scientific Committee of the University of Murcia (Spain) (ID: 1551/2017), and written informed consent and assent was obtained from parents and participants.

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Declaration of competing interest

None declared.

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