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Original Article

Criterion-related validity of 2-Dimensional measures of hip, knee and ankle kinematics during bilateral drop-jump landings

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Abstract: Three-dimensional (3D) motion capture systems have been used to identify athletes in high risk of injury, but due to their cost, lack of portability and qualified technicians, an alternative is needed, such as two-dimensional (2D) systems. The purpose of this study was to examine the criterion-related validity of three measures of frontal plane knee alignment (frontal plane projection angle [FPPA], knee-to-ankle separation ratio [KASR] and knee medial displacement [KMD]) and three sagittal plane measures (hip, knee and ankle flexion ranges of motion [RoMs]), recorded simultaneously using a 2D video analysis procedure and a 3D motion analysis system. Twenty-nine male futsal players had frontal and sagittal plane kinematics assessed while performing bilateral drop vertical jumps (DVJ). The criterion-related validity of the frontal and sagittal plane kinematic measures obtained using the 2D video analysis procedure and 3D motion system was determined through the estimation equation, typical error of the estimate (TE_{EST}) and validity correlation (r). Kappa correlations were also calculated to determine the agreement between the 2D and 3D kinematic approaches. The results showed poor validity for the FPPA measure (standardized TE_{EST} = 1.57 [large], r = 0.54) and ankle flexion RoM (standardized TE_{EST} = 2.48 [large], r = 0.37) and moderate validity for KASR (standardized TE_{EST} = 0.88 [moderate], r = 0.77), KMD (standardized TE_{EST} = 0.44 [small], r = 0.91), hip flexion RoM (standardized TE_{EST} = 0.67 [moderate], r = 0.83) and knee flexion RoM (standardized TE_{EST} = 0.58 [small], r = 0.87) measures. However, only the KMD and knee flexion RoM measures showed high levels of agreement (kappa > 0.7). Therefore, the KMD and knee flexion RoM measures calculated during a bilateral DVJ and using a 2D video analysis procedure might be considered as valid and feasible alternatives to their respective 3D criterion to quantify knee kinematics and to detect futsal players who demonstrated aberrant movement patterns in the frontal and sagittal planes, respectively.

Keywords: Dynamic knee valgus; injury; screening; motion analysis.

1. Introduction

Knee injuries are common among individuals participating in team sports (e.g.: football [Waldén et al., 2011], futsal [Junge & Dvorak, 2010], basketball [Agel et al., 2005] and rugby [Janssen et al., 2012]). In most cases, knee injuries (including anterior cruciate ligament [ACL] tears) occur in athletes by non-contact mechanisms (Boden et al., 2000; Hewett et al., 2006; Ireland, 1999; Starkey, 2000). In males, prior studies based on systematic video analysis have identified several situational patterns for team sport athletes (mainly in football [Della Villa et al., 2020; Waldén et al., 2015], handball [Olsen et al., 2004] and rugby [Montgomery et al., 2018] match-play) who have suffered a non-contact knee injury, including: 1) pressing and tackling, 2) regaining balance after kicking, 3) side-stepping and 4) landing from a jump. Although non-contact knee injuries are considered multifactorial in nature (Bittencourt et al., 2016), the adoption of an excessive dynamic valgus motion at the knee (a multi-joint and multiplane movement pattern comprised of varying degrees of hip adduction and internal rotation and knee abduction and external rotation joint kinematics [Powers, 2010]) during the execution of these high intensity weight-bearing dynamic tasks has been identified as the main injury pattern (Hewett et al., 2006; McLean et al., 2005; Myer et al., 2015). Furthermore, it has been documented that altered movement patterns in the sagittal plane (i.e., increased knee valgus, high vertical ground reaction force and external knee abduction moment, etc.) may also produce increased loading of the knee (Dai et al., 2014; Koga et al., 2018; Leppänen, Pasanen, Krosshaug, et al., 2017). In particular, stiff landings (i.e. landing from a jump with limited hip, knee and ankle flexion angles) (Pollard et al., 2010) will likely lead to less energy absorption in muscles and higher energy transmission to passive elements of the knee (Dai et al., 2014; Koga et al., 2018; Leppänen, Pasanen, Krosshaug, et al., 2017). Therefore, pre-participation assessment of hip, knee and ankle joints kinematics during dynamic tasks might aid in the identification of athletes who adopt inappropriate movement patterns associated with an increased risk of knee injuries (Shultz et al., 2015).

Three-dimensional (3D) motion analysis systems have been considered the criterion measurement to assess lower extremity joints kinematics during potentially high-risk tasks (e.g.: landing from a jump and cutting) related to knee injuries (mainly ACL) (Chung & Ng, 2012; Hewett et al., 2005; McLean et al., 2005; Myer et al., 2015; Paterno et al., 2010). However, the use of 3D motion analysis systems is often restricted to research settings and not used in applied environments or for pre-participation screening because of their high cost, lack of portability, time constraints and the need for sophisticated instruments and qualified technicians (McLean et al., 2005; Willson & Davis, 2008). Consequently, cost-effective, technically undemanding and portable alternative measurements to 3D motion analysis are needed. A low-cost, portable and readily available alternative to screen lower extremity joint kinematics might be the two-dimensional (2D) video analysis procedures where standard video cameras are used to capture performance of dynamic tasks. These are then imported into software packages (e.g.: Kinovea, Quintic, ImageJ and DartfishTM) that perform kinematic analysis in a plane perpendicular to the camera lens (Norris & Olson, 2011). However, the criterion-related validity of their measures must be determined before these 2D video analysis procedures can be used as objective and feasible alternatives to the 3D motion analysis systems to quantify lower extremity joints kinematics and to identify athletes who adopt potentially hazardous movement patterns during dynamic tasks (Hopkins, 2000).

Few studies have examined the criterion-related validity (mainly through correlation coefficients) of frontal plane knee alignment (i.e.: frontal plane projection angle of the knee [FPPA] [Gwynne & Curran, 2014; Mizner et al., 2012; Ortiz et al., 2016] and knee-to-ankle separation ratio [KASR] [Mizner et al., 2012; Ortiz et al., 2016]) during dynamic tasks (mainly drop landings), especially using 2D video analysis procedures and 3D motion analysis systems simultaneously. In particular, the measures of frontal plane knee alignment obtained through the use of 2D video analysis procedures have exhibited moderate to excellent correlation coefficients (r scores ranging from 0.64 to 0.96) with their respective 3D criterion measures (Gwynne & Curran, 2014; Mizner et al., 2012; Ortiz et al., 2016).

On the other hand, only Myer et al. (2010) have analysed the criterion-related validity of lower extremity kinematic measures obtained simultaneously through 2D video analysis procedures and 3D motion analysis systems in planes other than the frontal plane. Myer et al. (2010) examined the knee flexion RoM in the sagittal plane during a bilateral drop jump showing a high correlation with an r score of 0.95. To the authors´ knowledge, the criterion-related validity of other kinematic measures in the sagittal plane, such as hip and ankle flexion angles at initial landing contact and RoMs, have not been explored.

Hopkins (2000) stated that the use of the correlation coefficients (e.g.: Pearson correlation and intraclass correlation coefficients) as the unique statistical outcome of validity only provides information regarding how well the observed value retains the true rank order of participants (i.e. consistency). Consequently, correlation coefficients do not provide any insight into the magnitude (error) and characteristics (non-uniform error vs. uniform error) of the difference between participants´ scores (e.g.: FPPA) for the criterion (e.g.: 3D motion analysis systems) and practical (e.g.: 2D video analysis procedures) measures or methods. Thus, it is not possible to determine whether both measures and methods can be used interchangeably and if the same cutoff scores can be used to detect altered lower extremity movement patterns during dynamic tasks that may place an athlete at increased risk of knee injury using traditional statistical methods. More contemporary statistical methods, such as the calculation of the estimation equation (i.e.: a linear regression equation to predict the values of the practical measure or method from the given values of the criterion measure or method) and typical error of the estimate (TE_{EST}) have not been taken into consideration yet. Determination of criterion-related validity of the previously mentioned kinematic measures using contemporary statistical measures may be important for clinicians and strength and conditioning specialists because it can be used a) to assess an athlete and to predict his/her criterion value to get an accurate indication of altered mechanics using the cutoff scores established for the criterion test (3D motion analysis system) and b) to compare the validity of different measures or assessment methods (Hopkins, 2000).

Therefore, the purpose of this study was to examine the criterion-related validity of three measures of frontal plane knee alignment (FPPA, KASR and KMD) and nine measures of sagittal plane kinematics (hip, knee and ankle flexion angles at initial contact as well as their respective peak values and RoMs) recorded simultaneously using a 2D video analysis procedure and a 3D motion analysis system during a bilateral drop landing and applying a contemporary statistical approach in elite futsal players. It was hypothesized that frontal knee alignment measures and sagittal plane hip, knee and ankle measures recorded simultaneously through a 3D motion analysis system (gold standard) and 2D video analysis procedure would demonstrate moderate to strong criterion-related validity.

2. Materials and Methods

Subjects — Twenty-nine elite male futsal players (years = 23.2 ± 4.2 y, body mass = 73.8 ± 6.9 kg and heigh = 1.8 ± 0.7 m) from three different teams (13 players belonging to two clubs engaged in the First [top] National Spanish Futsal division and 16 players from two clubs engaged in the Second National Futsal division) completed this study. Futsal is a variant of football (soccer) played on a hard court, smaller than a football pitch and mainly indoors. To be included, all players had to be free of pain and injury at the time of testing (self-reported). Before any participation, experimental procedures and potential risks were fully explained to the players in verbal and written form, and written informed consent was obtained from all of them. An Institutional Research Ethics committee approved the study protocol prior to data collection (DPS.FAR.01.14) conforming to the recommendations of the Declaration of Helsinki.

Procedure — Prior to testing, each athlete performed a standardized dynamic warm-up (Taylor et al., 2009). The overall duration of the entire warm-up was approximately 20 min. After the warm-up, a 3-5 min rest was given for rehydrating and drying their sweat. Then, each player practiced the experimental task (bilateral drop vertical jump [DVJ]) three to five times. After the practice trials, players were prepared for data collection. Thus, the anthropometric measures required by the ViconTM (Vicon Motion Systems Inc., Denver, CO, USA) Plug in Gait Full Body model were first taken. After that, 35 reflective markers were placed on the skin with double-sided adhesive tape on each players anatomic landmarks according to the model´s instructions (Kadaba et al., 1990).

The Plug in Gait model has been used extensively in applied and research settings for many years to conduct kinematic analyses during dynamic tasks (including landing maneuvers) (Hughes et al., 2008; Leporace et al., 2020; Sell et al., 2019). As a direct kinematic and hierarchal method, the Plug in Gait model relies on the appropriate palpation and correct placement of retro-reflective markers along the predefined external anatomical landmarks capable of tracking body movements in order to compute joint kinematics (Sutherland, 2002). Given the reality of experimental conditions with different testers and a succession of individuals to assess, this may be a serious issue (Baudet et al., 2014). Thus, minor changes of marker placements modify the orientation of the coordinate systems and thereafter may lead to errors in joint kinematic outputs (France & Nester, 2001; Groen et al., 2012). This type of error is known as the kinematic "cross-talk" effect, which particularly affects the kinematics of joints that articulate principally around one major component (e.g. the knee joint). In order to minimize the errors caused by improper marker placement, the same tester who was a sport scientist with more than 10 years of experience in human movement analysis (IR-P) was responsible for marker placement in all bilateral landings kinematic assessments carried out in a controlled laboratory environment. 2D and 3D data were captured simultaneously while players completed each trial of the experimental task in a laboratory setting. Futsal players were examined wearing sports shorts and shoes.

Bilateral drop vertical jump — A DVJ was performed according to Onate et al. (2010). Briefly, players stood with feet shoulder-width apart on a 40 cm high box. They were instructed to lean forward and drop from the box as vertically as possible. Players were required to land with both feet simultaneously on a force platform (90x60 cm) that was located 20 cm in front of the box (with the purpose of serving as a reference object for the 2D video analysis system and to defined the landing phase of each DVJ for the 3D motion analysis system), then immediately perform a maximal vertical jump, finally landing back on the force platform. Each player performed three maximal jumps, starting from a standing position with at least 30 s of recovery between jumps. Players were asked to jump as high as possible. Players were allowed to use the arms and were able to choose the amplitude and speed of the countermovement needed to achieve the maximum high during the jump.

Instrumentation — A motion capture system with seven T10 cameras (Vicon MX; Oxford Metrics Group, Oxford UK) sampling at 200 Hz and a Kistler 9287 force platform embedded into the floor (Kistler, Winterthur, Switzerland), sampling at 1000 Hz, were used to simultaneously collect 3D kinematic and kinetic variables during the first landing of the three DVJs.

Two commercially available HD cameras (Panasonic Lumix DMC-FZ 200) sampling at a frequency of 200 Hz were also used to capture players´ performance during the DVJs. The cameras were placed at a distance of 4 m from the player and at the height of 1 m, one perpendicular to the frontal plane and the other perpendicular to the sagittal plane.

Data reduction—

3D data — A static standing calibration trial was completed before each data collection session started in order to determine the anatomical segment coordinate systems. Marker trajectories were identified with Vicon Nexus v1.8 software based on the participant's anthropometric measurements, participant's calibration, and system calibration (global coordinate system) and kinematic data (i.e. hip, knee and ankle joint angles in the sagittal, frontal and transverse planes) were obtained using Plug in Gait Full Body model. A double 2nd order Butterworth filter with a cutoff frequency of 6 Hz was used to filter marker coordinates.

The measures of frontal plane knee alignment FPPA and KASR were recorded at the time of maximum knee flexion during the first landing immediately after stepping off from the box and following the methodology described by Mizner et al. (2012). The frontal plane KMD measure and the sagittal plane hip, knee and ankle flexion RoMs were also calculated from the hip, knee and ankle flexion at initial contact with the ground to the maximum knee flexion angle during the landing phase in their respective planes. Similar to previous studies, the start of the landing phase of each DVJ (i.e. initial contact) was defined as the instant when the unfiltered ground-reaction force exceeded 20 N (McMahon et al., 2016). Maximum knee flexion angle was defined as the maximum angle between the thigh and shank segments during the ground contact phase. A positive value in ankle flexion corresponds to a dorsi-flexed ankle whereas a negative value represents a plantar-flexed ankle.

2D data —The digital videos recorded by the HD cameras from each DVJ trial were uploaded into Kinovea 0.8.25 software for conversion to still images. Kinovea software allowed to calculate all measures of frontal plane knee alignment and sagittal plane hip, knee flexion and ankle RoMs. The same investigator with extensive experience of using the software (IR-P) calculated all measures on three different occasions with the mean value used for further analysis. For the 2D video analysis, initial contact of the first landing phase was defined as the first frame in which ground contact was observed while maximum knee flexion angle was defined as the frame before the player started to extend the knee in order to perform the maximum vertical jump. For the variables measured in distance in the frontal plane, the images were calibrated using the width of the platform (90 cm). As participants were free to land closer or further away from the platform, to reduce perspective errors we calibrated the platform's width just where the tip of the toes touched the ground. Previous studies used reflective markers on bony landmarks (including joints centre) to guide the calculation of the 2D measures of frontal plane knee alignment (Gwynne & Curran, 2014; Herrington et al., 2017; Ortiz et al., 2016; Sorenson et al., 2015; Willson & Davis, 2008). 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 10 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 RoMs obtained during drop vertical landings both 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. On the contrary, 3D systems calculate the centre of the joints and the error in the motion analysis associated with movement of the markers is lower. Consequently, and with the aim of making the data reduction process more time-efficient and improving the agreement of the 2D kinematic measures with their respective 3D criterion, no markers were used over bony landmarks to guide the calculation of the 2D frontal plane measurements.

FPPA was calculated for the left leg with the videos of the frontal camera. To measure the FPPA, the investigator first created a femoral segment by placing a straight line that bisected the thigh outline, terminating at the investigator's estimation of the bisection of the femoral epicondyles. 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 shank segment began at the termination of the thigh segment and bisected the borders of the lower leg terminating at the estimated position of the ankle's lateral malleolus. 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. The angle formed by these two segments was then measured and used for analysis (Figure 1a). A measurement of 0° represents a neutral position of the knee in the frontal plane; whereas negative values represent a 2D knee valgus angle, and positive values represent a 2D knee varus angle.

KASR was calculated following the procedure described by Mizner et al. (2012) Thus, this measure was determined from the frontal view, by drawing a horizontal line between the visual estimation of the centres of the knee (knee separation distance) and another horizontal line between the estimation of the centres of the ankles. The length of each line was measured and the ratio between the length of the knee line and the length of the ankle line was finally recorded (figure 1b). A value of 1 represents an alignment of the knees directly on the ankles. A value less than 1 will occur when the centres of the knees are closer than the centres of the ankles, which have been suggested that represent 2D knee valgus. A value higher than 1.0 represented that knees were lateral to ankles, which have been suggested that represent 2D knee varus.

KMD was quantified as the displacement (in centimeters) of the visually estimated centre of the left knee during two different times of the landing phase (Myer et al., 2012). First measurement was during the initial contact phase (d1) and the second when the player reached maximal peak knee flexion during the ground contact phase (d2) (Figure 1c). Thus, the KMD was expressed as the displacement measure between the 2 marked knee alignments (d2 – d1). Negative and positive values denoted 2D valgus and varus alignments, respectively

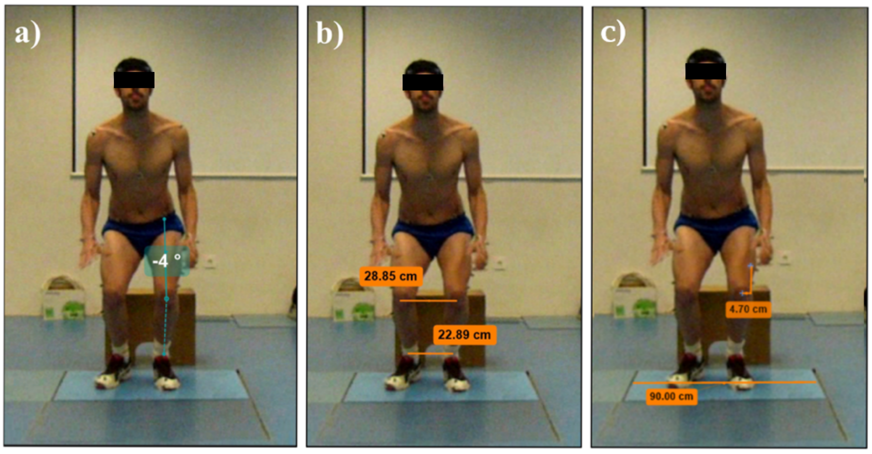

Figure 1. Frontal view 2D analysis.

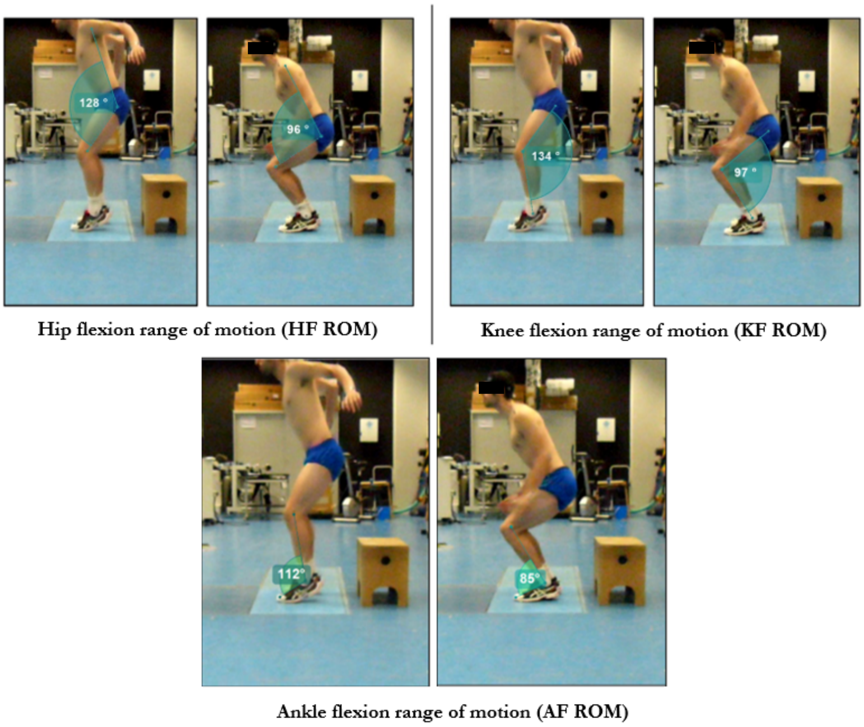

Figure 2. Lateral view 2D analysis. Note: angles were modified for the analysis in order to have the same references as 3D system

The sagittal plane camera was used to capture and quantify hip, knee and ankle flexion angle at initial contact, peak values and RoMs on the left leg. Peak hip, knee and ankle flexion angles and RoMs were calculated in the first video frame in which ground contact was observed and maximum knee flexion. Hip flexion angle was defined as the angle formed by a straight line joining the medial part of the thigh originating in the lateral femoral epicondyle marker and the straight line joining the estimated hip rotation axis with the projection of the spine in neutral position (Figure 2). Knee flexion angle was considered the angle formed by the straight lines of the thigh, as previously described, and leg segments, joining the lateral femoral epicondyle and the lateral malleolus marker (Figure 2). Ankle flexion angle was described as the angle formed between the lateral femoral condyle and the lateral malleolus line and a line between the lateral malleolus and the 5th metatarsal head (Howe et al., 2019).

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 SDs were calculated for each measure. Inter-trial reliability of the 2D and 3D measurements were assessed using ICC_{3k}. Intra-tester reliability of the 2D measurements was also evaluated through ICC_{2k}. In particular, the tester extracted all the 2D measures from one third of the video recorded on three different occasions with a two-week interval between consecutive moments. Magnitudes of ICC were classified according to the following thresholds: poor, <0.49; moderate, 0.5 to 0.74; good, 0.7 to 0.89; and excellent, >0.9 (Munro et al., 1986).

The criterion-related validity of each measure was determined through an estimation equation, TE_{EST} and validity correlation (Pearson coefficient) using the method previously descried by Hopkins (2000). The estimation equation was calculated as the equation generated by plotting and after fitting a straight line to 3D data against 2D data ($y = slope \cdot X + intercept$). The TE_{EST} was calculated as the mean typical error of the difference between the 3D and 2D data reported by the players. To interpret the TE_{EST} values, Hopkins (2000) suggests calculating the standardized TE_{EST} (TE_{EST}/SD of the criterion test [3D motion analysis]) and then using the following arbitrary values: <0.2 trivial, 0.2 to 0.6 small, >0.6 to 1.2 moderate, >1.2 to 2.0 large, and >2.0 very large. Validity correlation was expressed through Pearson correlation coefficients (r) between the 3D data and the 2D data. Magnitudes of correlations were assessed using the following scale of thresholds: <0.80 low, 0.80 to 0.90 moderate, and >0.90 high (Hopkins, 2000).

The assessing agreement (systematic bias and random error) between the 3D and 2D measures was calculated using the statistical methods described by Bland and Altman (1986). Heteroscedasticity was checked by analysing the degree of correlation between the residuals and predictive values (Hopkins, 2000).

Additionally, the measures of frontal plane knee alignment were dichotomized to indicate a positive or negative score for each player based on the presence of dynamic knee valgus or varus. Although limited hip, knee and ankle flexion kinematics in the sagittal plane have been associated with an increased risk of knee injury (Fong et al., 2011; Koga et al., 2018; Leppänen, Pasanen, Krosshaug, et al., 2017; Leppänen, Pasanen, Kujala, et al., 2017) no specific cutoff scores have been defined yet (from the authors´ knowledge). Consequently, in the absence of robust cut-off scores for identifying athletes at high risk of loading the knee joint, the average hip, knee and ankle flexion angles at initial contact, peak values and RoM scores reported for injured players by prospective studies aimed at investigating the relationship between selected sagittal plane hip, knee and ankle kinematic and the risk of ACL injury (Ardern et al., 2011; Della Villa et al., 2020; Koga et al., 2018; Leppänen, Pasanen, Krosshaug, et al., 2017; Paterno et al., 2010), alongside the authors´ extensive experience in screening athletes, were used to finally define the following cutoff score to indicate a high or low risk of loading the knee joint: <50 (low risk) and >50º (high risk) for hip and knee flexion RoM measures, <30 (high risk) and >30 (low risk) for ankle RoM, <35 (high risk) and >35º (low risk) for hip angle at initial contact, <25 (high risk) and >25º (low risk) for knee angle at initial contact, <-6 (high risk) and >-6º (low risk) for ankle flexion at initial contact, <90 (low risk) and >90º (high risk) for peak hip flexion angle, <95 (low risk) and >95º (high risk) for peak knee flexion angle, and <40 (low risk) and >40º (high risk) for ankle peak angle. After reducing the data to binary variables, Kappa correlations (k) were calculated to determine the percent agreement between the two techniques (3D motion analysis and 2D video analysis) of kinematic analysis to discriminate participants with a positive (dynamic knee valgus or high risk of loading the knee) and negative (dynamic knee varus or low risk of loading the knee) diagnosis. Magnitudes of k correlations were assessed using the following scale of thresholds: <0.20 poor; 0.20-0,40 fair, 0.41-0.60 moderate, 0.61-0.80 high and 0.81-1.00 very high (Landis & Koch, 1977).

It has been suggested that the requirements needed to consider that a practical measure or method presents an acceptable or good criterion-related validity for research and practical goals must be context-specific (Hopkins, 2000). No studies (to the authors´ knowledge) have defined the requirements needed to infer that a 2D kinematic measure demonstrates good criterion-related validity with respect to its respective gold standard 3D measure using the comprehensive approach of this study. Consequently, the current study established the following requirements: standardized TE_{EST} < 1.2 (moderate as maximum), r > 0.8 (at least moderate) and k statistics > 0.6 (at least high).

Data were analysed using SPSS for Windows, Version 20.0 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel spreadsheet (www.sportsci.org).

3. Results

Mean values for each of the 2D and 3D outcome measures are presented in Table 1. Data for all 2D and 3D measures showed high to excellent inter-trial reliability, with ICC values ranging from 0.90 to 1. Consequently, data of the three recorded trials were averaged for further analysis. Furthermore, intra-tester reliability for the 2D kinematic measures ranged from good to excellent (ICCs from 0.85 to 0.97).

Validity measures are presented in Figure 3 for frontal plane knee joints alignment variables and in figures 4, 5 and 6 for sagittal plane hip, knee and ankle flexion angles and RoMs, respectively. Poor validity scores were found for the measure of frontal plane knee alignment FPPA (standardized TE_{EST} = 1.57 [large] and r = 0.54 [low]), moderate to high validity scores were found for KASR (standardized TE_{EST} = 1.00 [moderate] and r = 0.71 [low]) and KMD (standardized TE_{EST} = 0.44 [small] and r = 0.91 [high]) measures. Likewise, moderate validity scores were obtained for the measures of hip (standardized TE_{EST} = 0.83 [moderate] and r = 0.77 [low]) and knee flexion (standardized TE_{EST} = 0.96 [moderate] and r = 0.72 [low]) angles at initial contact, peak hip (standardized TE_{EST} = 0.64 [moderate] and r = 0.84 [moderate]) and knee (standardized TE_{EST} = 0.39 [low] and r = 0.93 [high]) flexion angles and hip (standardized TE_{EST} = 0.67 [moderate] and r = 0.83 [moderate]) and knee (standardized TE_{EST} = 0.58 [small] and r = 0.87 [moderate]) RoMs. Poor validity scores were observed for the sagittal plane ankle flexion angles recorded at initial contact (standardized TE_{EST} = 3.24 [very large] and r = 0.29 [low]) and peak knee flexion (standardized TE_{EST} = 4.72 [very large] and r = 0.21 [low]) and also its RoM (standardized TE_{EST} = 2.48 [very large] and r = 0.37 [low]).

Bland-Altman plots (supplementary files S1-S4) confirmed that all measures of frontal plane knee alignment (FPPA = 12.0 ± 21.9º, KASR = -0.16 ± 0.28, KMD = -0.9 ± 1.6 cm) and four sagittal plane hip, knee and ankle flexion angles (knee and ankle angles at initial contact = -8.4 ± 8.3º, -25.7 ± 10º, respectively; peak hip and ankle angles = 11.2 ± 9.1º, -33.3 ± 12.9º, respectively) and one RoM (hip flexion RoM = 12.1 ± 10.9º) showed systematic bias ($p < 0.05$) between 3D motion analysis and 2D video analysis. Furthermore, no statistically significant associations between predictive and residual scores were found for all paired kinematic measures (uniform error).

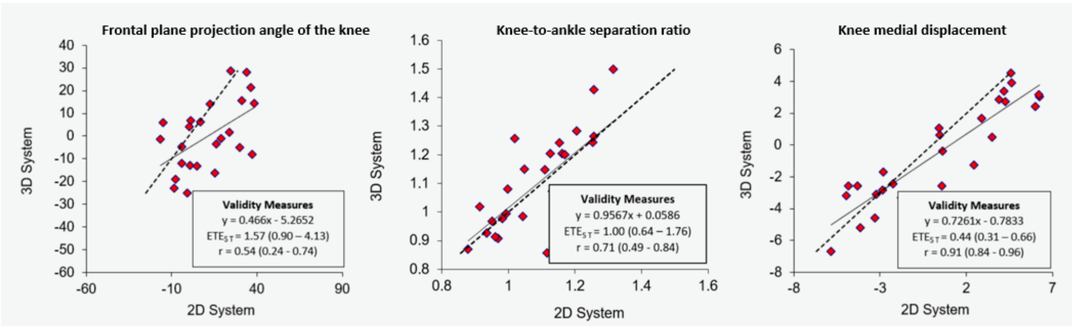

Figure 3. Validity measures of the frontal view variables: FPPA, KASR and KMD.

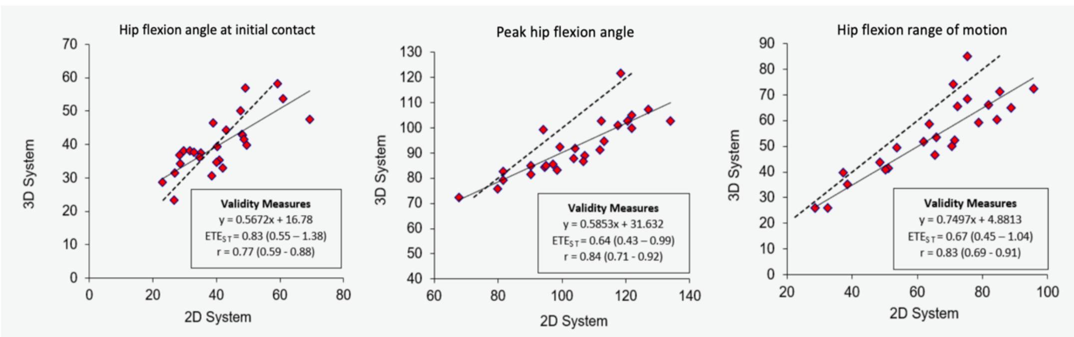

Figure 4. Validity measures of hip flexion variables: hip flexion angle at initial contact, peak hip flexion angle and hip flexion range of motion.

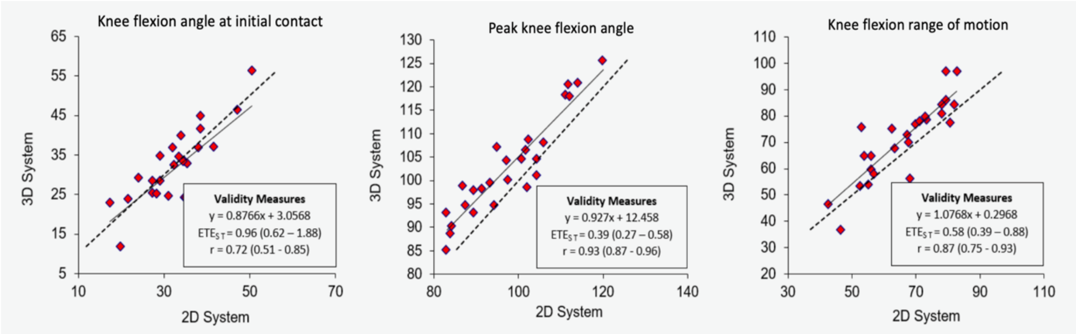

Figure 5. Validity measures of knee flexion variables: knee flexion angle at initial contact, peak knee flexion angle and knee flexion range of motion.

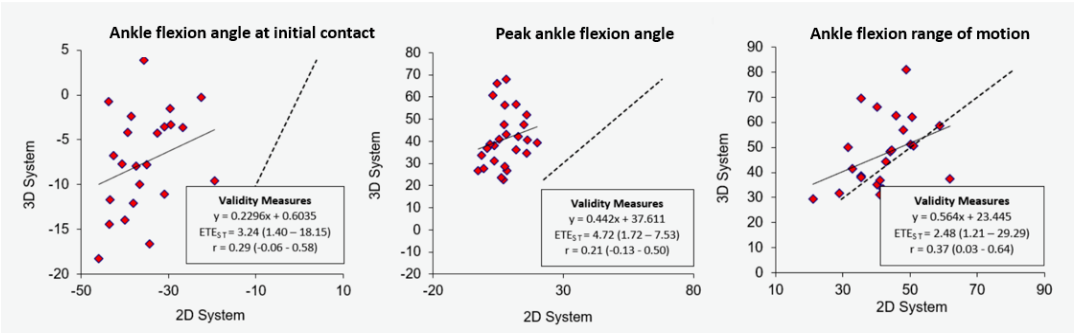

Figure 6. Validity measures of ankle flexion variables: ankle flexion angle at initial contact, peak ankle flexion angle and ankle flexion range of motion.

Table 1. Mean values for 3D and 2D variables during bilateral drop vertical jumps (DVJ).

Measures	3D (mean ± SD)	2D (mean ± SD)
Frontal plane knee alignment		
FPPA (º) (+ varus, - valgus)	1.8 ± 17.0	11.3 ± 17.0
KASR	1.1 ± 0.2	1.1 ± 0.1
KMD (cm) (+ varus, - valgus)	-0.5 ± 3.2	0.4 ± 4.0
Sagittal plane lower extremity joints alignment (º)		
Hip flexion		
▪ Initial contact	39.9 ± 8.5	40.8 ± 11.5
▪ Peak angle	92.2 ± 11.3	103.4 ± 16.3
▪ RoM	53.0± 16.3	63.0 ± 18.6
Knee flexion		
▪ Initial contact	31.9 ± 9.5	32.9 ± 7.8
▪ Peak angle	103.3 ± 10.6	98.0 ± 10.6
▪ RoM	71.1 ± 14.8	65.3 ± 11.8
Ankle flexion (+ dorsiflexion, - plantar flexion)		
▪ Initial contact	-7.4 ± 5.6	-35.0 ± 7.2
▪ Peak angle	41.0 ± 12.7	7.6 ± 6.0
▪ RoM	47.3 ± 13.9	42.3 ± 9.2

2D: two-dimensional; 3D: three-dimensional; SD: standard deviation; FPPA: frontal plane projection angle; KASR: knee-to-ankle separation ratio; KMD: knee medial displacement; HF: hip flexion; KF: knee flexion; RoM: range of motion; IC: initial contact.

Table 2 demonstrates the Kappa agreement among measures. Only the KMD and peak knee flexion angle and RoM measures showed moderate to high levels of agreement (k > 0.6, p < 0.05).

Table 2. Kappa correlations

	FPPA	KASR	KMD	HF IC	HF PA	HF RoM	KF IC	KF PA	KF RoM	AF IC	AF PA	AF RoM
FPPA	0.331*											
KASR		0.124										
KMD			0.772*									
HF IC				0.283								
HF PA					0.308*							
HF RoM						0.581*						
KF IC							0.435*					
KF PA								0.669*				
KF RoM									0.780*			
AF IC										0.133		
AF PA											0.100	
AF RoM												0.458*

FPPA: frontal plane projection angle; KASR: knee-to-ankle separation ratio; KSD: knee separation distance; KMD: knee medial displacement; HF: hip flexion; KF: knee flexion; AF: ankle flexion; ROM: range of motion; IC: initial contact; PA: peak angle. *: p < 0.05.

4. Discussion

The main findings of the current study indicate that the measure of frontal plane knee alignment FPPA calculated during a bilateral DVJ, using a 2D video analysis procedure, presented poor criterion-related validity (standardised TE_{EST} = 1.57 [large], r = 0.54 [low] and k = 0.31 [poor]) compared with a 3D motion analysis system. These findings were similar to those reported in previous studies (Ortiz et al., 2016; Sorenson et al., 2015), although not all (Mizner et al., 2012), using only the Pearson coefficient (validity correlation) as an indicator of validity and a DVJ as the experimental task. For example, Ortiz et al. (2016) found Pearson correlation values of r = 0.39 and 0.57 between the FPPA scores obtained concurrently through a 2D video analysis procedure and a 3D motion analysis system, for the dominant and non-dominant legs respectively. A plausible explanation for the poor validity scores found for the FPPA obtained using 2D video analysis procedures might be based on the fact that this measure is a combination of frontal and transverse plane motions of the hip and knee and this may lead to a perspective error as standard cameras have the limitation (among others) of only recording uniplanar images placed transversally to their lens. Furthermore, the hip and knee multiplanar movements executed during the DVJ may have made the visual identification of the anatomical landmarks and the subsequent process of drawing lines (bisectors) that are needed to determine the angulation of both segments difficult, which may have also led to an increase in the measurement error. The results of the present study also reported that the 2D video analysis system showed statistically significant overestimation of the FPPA scores when they were compared with their 3D criterion measures (mean systematic bias = 12 ± 21.9º; effect size = 0.58 [small]).

Ortiz et al. (2016) also found that the 2D video analysis techniques overestimate the true values (defined by the 3D motion analysis system) of the FPPA kinematic measure by approximately 7º, which is comparable, albeit lower than the 12º reported in the current study.

In the scientific literature, some studies have examined the criterion-related validity of the FPPA measure obtained simultaneously using 2D and 3D systems during functional tasks (such as running (Maykut et al., 2015), single leg squat (Gwynne & Curran, 2014; Herrington et al., 2017; Sorenson et al., 2015; Willson & Davis, 2008) and lateral side step (McLean et al., 2005)). These studies demonstrate slightly higher Pearson correlation scores between the 3D and 2D analysis for the FPPA than those found when DVJ tasks were used. Gwynne & Curran (2014) and Herrington et al. (2017) reported correlation values of r = 0.78 and 0.79 between the 3D and 2D systems for FPPA recorded at 60º and 45º of knee flexion while participants adopted a single leg squat testing position. However, the clinical relevance of these 2D FPPA measures obtained during slow functional tasks might be lower than the FPPA measures obtained during explosive sport-related dynamic tasks, such as landings and cutting maneuvers, that more accurately reflected both the situational patterns and injury mechanism of the knee (i.e. excessive dynamic knee valgus) in team sport athletes (Krosshaug et al., 2007; Olsen et al., 2004).

Regarding the two other measures of frontal plane knee alignment (KASR and KMD), the results of this study showed that there were moderate standardized TE_{EST} and r scores between the 2D and 3D systems for both kinematic measures. Similar Pearson correlation values between the 2D and 3D systems were found by Myer et al. (2010) and Ortiz et al. (2016) for the KMD measure (r > 0.85). Although the findings of the present study also report the presence of systematic bias between the scores of both systems (2D video analysis procedure and 3D motion analysis system) and for the KASR (systematic bias = -0.16 ± 0.28; effect size = 0.39 [small]) and KMD measures (systematic bias = 0.9 ± 1.6 cm; effect size = 0.24 [small]), their magnitudes (i.e. effect sizes) may be considered as small according to the cutoffs described by Cohen (1988). However, and in contrast to that observed for the KMD measure, the measurement error of the 2D KASR, although small and homoscedastic, was big enough to generate disagreement between both systems (Kappa correlation = 0.12) based on either knee valgus or varus during the DVJs and hence, these measures should not be used interchangeably. Therefore, the KMD was the only measure of frontal plane knee alignment that satisfied the three requirements (standardized TE_{EST} < 1.2, r > 0.8 and k > 0.6) that were established to considerer a 2D kinematic measure as having acceptable criterion-related validity for research and practical purposes (standardized TE_{EST} = 0.44 [small], r = 0.91 [high] and k = 0.77 [high]). A reason that might partially explain why the KMD showed the highest validity scores in comparison with the other two measures of frontal plane knee alignment could be based on the fact that the calculation process using 2D video analysis is easier. Thus, and in order to calculate the KMD, clinicians and strength and conditioning specialists only need to visually identify an anatomic landmark (centre of the knee) and quantified the displacement (in centimeters) during two different time points within the landing phase. Contrarily, the quantification of the KASR requires the identification of more anatomic landmarks (centres of the knee and ankle) while the FPPA measure needs not only the identification of anatomic landmarks but to visually create femoral and shank segments by placing straight lines that bisect the thigh and the borders of the lower leg, respectively.

On the other hand, the findings of this study also showed moderate to low standardized TE_{EST} and moderate to high r scores for the hip and knee flexion angles at initial contact, peak hip and knee flexion angles and hip and knee RoM measures using the 2D video analysis technique compared with the 3D data capture. However, poor validity scores (standardized $TE_{EST} > 2$, $r < 0.4$) were found between the ankle flexion kinematic measures obtained simultaneously from the 2D and 3D systems. A reason that may explain these poor validity scores of the 2D ankle kinematic measures is based on the fact that when measuring the ankle flexion angle in the 2D analysis system, the researcher must guess the exact position of the foot, which may be influenced by the participants footwear. However, the 3D system will take all the marker data and process it with an internal model generating positions of limb segments and then find the angle between these segments (Eltoukhy et al., 2012). Slightly higher correlational results were reported by Myer et al. (2010) for knee flexion RoM (r = 0.95). As the current study has been the first (to the best of the authors´ knowledge) to explore the criterion-related validity of the sagittal plane hip, knee and ankle flexion angles and hip and ankle RoM measures, comparisons with previously published works were not possible. Similar to that found for the measures of frontal plane knee alignment, the presence of systematic bias was also reported in four sagittal plane hip, knee and ankle flexion angles (knee and ankle angles at initial contact = -8.4 ± 8.3º [effect size = 0.12], -25.7 ± 10º [effect size = 3.08], respectively; peak hip and ankle angles = 11.2 ± 9.1º [effect size = 0.83], -33.3 ± 12.9º [effect size = 0.43], respectively) and one RoM (hip flexion RoM = 12.1 ± 10.9º [effect size = 0.59]). For all the sagittal plane kinematic measures, the systematic errors between both systems were homoscedastic (similar in magnitude for the higher and lower scores). The magnitudes of the systematic and uniform bias observed in these sagittal plane kinematic measures were large enough to generate numerous disagreements (k < 0.6) between the 2D video analysis procedure and 3D motion analysis system in the identification of participants exhibiting (or not) hip, knee and ankle flexion angles and RoMs during a bilateral drop landing that might be associated with increased knee loading. Only the peak knee flexion angle (k = 0.67) and knee flexion RoM (k = 0.78) measures showed clinically acceptable Kappa agreement scores between the 2D and 3D systems. Consequently, the 2D peak knee flexion angle and knee flexion RoM measures in the sagittal plane might be considered as valid and feasible alternatives to the respective 3D criterion, as they fulfilled the three requirements established.

This study is not without limitations. First, the criterion-related validity of the 2D measures was only examined in uninjured futsal players and further studies are required to identify if these or different validity scores would occur in other cohorts of athletes with and without knee injuries. Second, all kinematic measures were recorded during a DVJ and hence, the validity scores cannot be generalizable to other dynamic tasks. Third, only the FPPA and sagittal measures for the left leg was calculated. While this was appropriate for the purpose of this study, it may be recommended that future studies assess the FPPA for both legs because an asymmetry in knee abduction angle between sides was found to be a predictor of ACL injury status (Hewett et al., 2005).

5. Practical Applications.

The main findings of the current study indicate that, unlike FPPA and KASR, the KMD measure calculated during a bilateral DVJ task and using a 2D video analysis procedure might be considered as a valid and feasible alternative to its respective 3D criterion for quantifying the frontal plane knee alignment of asymptomatic futsal players. Likewise, the results of this study also support the use of 2D video analysis procedures to quantify the peak knee flexion angle and knee flexion RoM during the landing phase of a DVJ. Therefore, futsal practitioners will have a portable and economic tool to screen players on the field and identify those that are at hight risk of suffering a knee injury.

Supplementary Materials: The following are available online at http://eurjhm.com/index.php/eurjhm, Figure S1: Bland and Altman plots showing individual differences between 2D and 3D system values plotted against the mean for FPPA, KASR and KMD variables, Figure S2: Bland and Altman plots showing individual differences between 2D and 3D system values plotted against the mean for hip flexion variables, Figure S3: Bland and Altman plots showing individual differences between 2D and 3D system values plotted against the mean for knee flexion variables, Figure S4: Bland and Altman plots showing individual differences between 2D and 3D system values plotted against the mean for ankle flexion variables.

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