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Published Version:
Di Paolo, S., Musa, F., D'Orsi, G.M., Grassi, A., Vulpiani, M.C., Zaffagnini, S., et al. (2024). A comprehensive two-dimensional scoring system to assess the single-leg squat task in football players. THE KNEE, 48, 52-62 [10.1016/j.knee.2024.02.016].

Availability:
This version is available at: https://hdl.handle.net/11585/1012238 since: 2025-08-26

Published:
DOI: http://doi.org/10.1016/j.knee.2024.02.016

A Comprehensive 2D Scoring System to Assess the Single-Leg Squat Task in Football Players

Running title: Association between 3D motion capture and 2D video-analysis

Stefano Di Paolo[1], Francesca Musa[2,3], Giovanni Maria d'Orsi[4], Alberto Grassi[1], Maria Chiara Vulpiani[2,3], Stefano Zaffagnini[1], Francesco Della Villa[4]*

1) 2nd Orthopaedic and Traumatologic Clinic, IRCCS Istituto Ortopedico Rizzoli

2) Department of Medical-Surgical Sciences and Translational Medicine, Sapienza University of Rome, Rome, Italy.

3) Unit of Physical Medicine and Rehabilitation, Sant'Andrea University Hospital, Via di Grottarossa 1035, Rome, Italy.

4) Education and Research Department, Isokinetic Medical Group, FIFA Medical Centre of Excellence, Via Casteldebole, 8/4, 40132, Bologna, Italy.

*** Corresponding Author:**

Stefano Di Paolo, Eng

2nd Orthopaedic and Traumatologic Clinic, IRCCS Istituto Ortopedico Rizzoli

Via Giulio Cesare Pupilli, 1, 40136 Bologna (BO), Italy

stefano.dipaolo@ior.it

ORCID ID: 0000-0002-1761-7352

Twitter: @StDiPaolo

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Abstract

*Background***:** The single leg squat (SLS) is a safe and widespread functional test commonly performed in the mid stages of rehabilitation after severe knee injuries. The use of reliable objective measures has been advocated to improve the quality of SLS assessment. The aim of the study was to describe a qualitative whole-body scoring system based on 2D video-analysis during SLS test and validate it against 3D kinetics and kinematics.

*Methods***:** Thirty-four competitive football (soccer) players performed a series of SLS tasks. 3D kinematics and kinetics were collected through infrared cameras, and 2D video-analysis was performed through a scoring system with sub-scores ranging from 0/2 (non-adequate movement) to 2/2 (adequate movement) based on frontal and lateral planes objective measurements. 3D kinematics and kinetics were grouped according to the results of the 2D evaluation and compared through the ANOVA ($p<0.05$).

*Results***:** Higher hip adduction, hip internal rotation, and knee valgus collapse were found in trials rated 0/2 or 1/2 compared to the one rated 2/2 in the Limb Stability score. Hip flexion and hip/knee moment ratio were lower in those scoring 0/2 compared to those scoring 2/2 in Movement Strategy. A low total score was associated with higher knee valgus collapse and lower hip/knee extensor moment ratio. Compensatory strategies were found in frontal plane scores.

Conclusions: The 2D scoring system described was strongly associated with kinematics and kinetics from gold standard 3D motion capture and might represent a valid tool to describe the movement quality of a SLS task.
Level of Evidence: Descriptive Laboratory Study

Keywords: 2D video-analysis, soccer, single-leg squat, return to sport, ACL injury prevention

1. Introduction

The incidence of knee injuries such as Anterior Cruciate Ligament (ACL) injury in professional football (soccer) is still high and has severe physical, psychological, and economic implications related to the intervention and the time spent off the field [1,2]. Abnormal joint biomechanics and poor neuromuscular control are among the most known risk factors for several knee pathologies [4,5]. Identifying high-risk athletes can be an important first step in planning specific training programs before and during the season aimed at reducing the rate of knee injuries [6].

The single leg squat (SLS) test is one of the most commonly used functional tests [7–9]. SLS is simple, safe, and can be easily performed in a clinical setting in the mid stages of rehabilitation after knee injuries [10]. Currently, the assessment of SLS test performance is often subjective and based on visual rating criteria [11,12]. Although such ratings have been validated over years [11,12], the use of objective biomechanical measures has been advocated to improve the SLS assessment, reducing the biases of visual observations [13]. Indeed, despite its low physical demand, the SLS requires synergy between the trunk, pelvis, hip, knee and ankle motion [8,10,11,14].

The 3D motion capture is considered the gold standard for quantitative movement analysis [15]. However, such a technology is often not worth the cost for low-demanding tasks or low volume rehabilitation centers. Thus, 2D video-analysis emerged as a cost-effective alternative with promising accuracy and reliability results [8,10,16–18].

Although several studies tested video-analysis tools for different 2D variables, a recent systematic review reported poor methodological quality and low reliability among the SLS tests [8]. Frontal plane kinematics, mostly assessed at knee level only, showed the most critical results in terms of agreement with gold standard 3D motion capture. Furthermore, to the date, no whole-body scoring systems has been provided, thus limiting the understanding of the potential interplay and compensations between lower limbs and pelvis-trunk complex both in primary prevention and in rehabilitation after knee surgery. Therefore, the aim of the present study was to describe a qualitative scoring system based on 2D video-analysis of sagittal and frontal plane during a single-leg squat tasks and validate it against kinetics and kinematics collected through 3D motion capture. The hypothesis was that the total score and sub-scores effectively identifies biomechanical risk factors for ACL injury in healthy young football players.

2. Materials and Methods

2.1 Participants

Thirty-four competitive football (soccer) players (age 22.8 ± 4.1, 16 females, Tegner 7-9) were enrolled in the study. Exclusion criteria were evidence of previous severe injury (> 28 days recovery time [2]); body mass index (BMI) > 35; previous surgery to lower limbs; cardiopulmonary or cardiovascular disorders; inability to perform the required tasks. Each participant signed informed consent before enrollment. The Institutional Review Board of *Blinded for Submission* approved the study (IRB approval: *Blinded for Submission*; ClinicalTrials.gov Identifier: *Blinded for Submission*).

2.2 Data collection

The data collection was conducted in *Blinded for Submission*. Each player was asked to perform a single leg squat. They were instructed to reach the maximum knee flexion angle and hold the position for three seconds before extending the knee back to the standing position. The foot of the bending leg was at the center of a force platform in neutral rotation; however, the foot rotation was not standardized among the participants to avoid inducing bias in the movement. No further movement constraints (e.g., hands and contralateral limb position) were provided in order to maximize players' comfortable posture. Dynamic warm-up and stretching were conducted before the test. Each player performed six valid trials (three right and three left squats). The validity of each trial was verified by a single sport & exercise medicine physician specialized in sports biomechanics (*Blinded for Submission*). Trials where position was not held for at least three seconds were discarded and repeated.

3D motion data was recorded through a set of 10 optoelectronic cameras, a force platform embedded in the floor (AMTI 400*600, Watertown, MA USA), and three high-speed cameras placed frontally and bilaterally towards movement direction (VICON Nexus, Vicon Motion Systems Ltd, Oxford, UK). The systems were synchronized for direct data comparison and data processing interpolation ensured the analysis at the same frame for both systems (sampling rate: 120 Hz for cameras and force platform, 100 Hz for the high-speed cameras).

The system calibration was performed at the beginning of the acquisition and repeated periodically during the session. Forty-two retroreflective markers were placed on each participant by a single expert user according to the full-body Plug-in Gait protocol (*https://docs.vicon.com/FullbodymodelingwithPlug-inGait*). Each participants' model calibration was performed before data collection.

2.3 Data Processing – 3D kinematics and kinetics

3D Kinematics and kinetics data were processed in the VICON Nexus software environment based on marker trajectories collected through the infrared cameras and the GRFs collected through the force platform. The knee and hip extensors moment were computed through VICON Nexus software using the standard “bottom-up” inverse dynamics approach of the Plug-in Gait protocol and normalized by each participant's body weight (N*m/BW). To the purpose of the present study, the following 3D kinematic and kinetic variables were investigated: knee varus-valgus (positive: varus), internal-external rotation (positive: internal), and flexion; hip abduction-adduction (positive: adduction), internal-external rotation (positive: internal), and flexion; valgus collapse (as defined by Arundale et al. [19]; hip/knee flexion angle ratio; pelvic lateral tilt (positive: contralateral drop) and rotation (positive: ipsilateral rotation); trunk lateral tilt (positive: contralateral tilt) and rotation (positive: ipsilateral rotation); hip/knee extensor moment ratio.

2.4 Data Processing – 2D video-analysis

The 2D video-analysis evaluation was performed in a proprietary VICON software environment through the recordings of the three high-speed cameras. The joint kinematics was computed on frontal and sagittal plane at the frame of maximal knee flexion angle to highlight potentially poor motor control [20–22]. For each trial, the following 2D angles were calculated (Figure 1): Frontal Plane Knee Projection Angle (FPKPA), Pelvis tilt Angle (PA), and Trunk tilt Angle (TA), α angle (supplementary knee flexion angle), β angle (supplementary hip-trunk flexion angle). Furthermore, each SLS trial received a score based on the previous 2D objective measurements. The scoring system was divided into four sub-criteria, limb stability (LS), pelvis stability (PS), trunk stability (TS), and movement strategy (MS). For each criterion, a sub-score of 0/2 (non-adequate), 1/2 (partially adequate), or 2/2 (adequate) was attributed to the movement [20–22]. The 2D total score was the sum of each sub-criteria, the best score possible is 8/8. The details of the 2D scoring system were reported in Figure 1.

2.5 Statistical analysis

The normal distribution of the data was verified through the Shapiro-Wilk test. The categorical variables were presented as a percentage over the total, while the continuous variables were presented as mean ± standard deviation (95% Confidence Interval – CI).

Each trial was grouped according to the score of each sub-criterion (Group 0, 1, 2). The ANOVA was used to investigate the statistical differences among the three groups, and the two-tails Student's t-test with Bonferroni correction for multiple comparisons was used to investigate the differences between the single groups. The η_p^2 effect size was reported alongside p-value. Effect size was considered small, medium, and large for η_p^2 0.01, 0.06, and 0.14, respectively.

The Person's correlation coefficient r was used to assess the correlation between the 2D and 3D kinematic and kinetic variables. The Spearman's rank correlation coefficient ρ was used to assess the correlation between the 2D total score and 3D kinematic and kinetic variables. Correlation was considered poor, moderate, and strong for r values <0.4, 0.4 – 0.75, and >0.75, respectively. Differences were considered statistically significant for $p<0.05$. All the statistical analyses were performed in SPSS (v26, IBM, Armonk, NY, US).

The presence of frontal plane compensations in 2D sub-scores was also inspected. A heatmap chart was provided to visualize clusters of 2D scores for LS, PS, and TS criteria (e.g., count of trials rated low LS – 0/2 and high TS – 2/2).

An a-priori power-analysis was performed in G*Power (v3.1, Brunsbüttel, Germany) based on the results of the systematic review by Warner and colleagues [8]. The minimum difference between groups in terms of FPKPA (4.1°, healthy vs knee injured athletes) and the largest standard deviation (9.6°) were extracted. Considering an ANOVA test among three groups, an *f* effect size of 0.34 was produced. Adopting a more conservative approach with an *f* effect size of 0.25, at least 159 trials were required to have a power of 0.8 and a type I error of 0.05. Considering the present study setting (6 valid trials per subject), a minimum sample of 27 subjects (162 trials) was required.

3. Results

Overall, 169 valid trials with complete 3D and 2D evaluation were included in the final analysis (descriptive results reported in Table 1). Trial exclusion (n=35) was made due to technical issues during the data acquisition or processing (partial or total loss of data, missing marker reconstruction, etc.). Significantly higher hip adduction (large effect), hip internal rotation (moderate effect), and valgus collapse (large effect) were found in trials rated 0/2 or 1/2 compared to the one rated 2/2 in the Limb Stability score ($p<0.022$, Table 2). Significant differences in hip abd-adduction were also found in terms of Pelvis and Trunk Stability scores (moderate effect, $p<0.001$, Table 2). Significantly lower hip flexion and hip/knee flexion angle ratio (large effects, $p<0.001$) were found in those scoring 0/2 compared to those scoring 2/2 in Movement Strategy (Table 3). Furthermore, hip extensor moment and hip/knee moment ratio were lower (moderate-to-large effects, $p<0.001$) in those scoring 0/2 (Table 3).

The FPKPA positively correlated with hip rotations and valgus collapse ($p<0.006$, Table 4). Significant correlations were found also between 2D and 3D pelvis and trunk angles and between α and β with knee flexion and hip flexion, respectively ($p<0.001$, Table 4). The β/α ratio correlate with hip/knee kinematics and extensor moment ratios ($p<0.001$, Table 4).

A higher total score was significantly correlated with lower knee valgus collapse, higher hip/knee extensor moment ratio (Figure 2), lower knee flexion, higher hip flexion, pelvic contralateral drop and pelvic contralateral rotation (Table Appendix A1).

Frontal plane compensation emerged from heatmap clustering of 2D scores: PS and TS scores were high (2/2) in those obtaining low LS score (0/2) and vice versa (Figure 3).

4. Discussion

The main finding of the present study was a strong association between the 2D video-analysis scoring system and the 3D kinetic and kinematics in the evaluation of the SLS test. Both 2D angles, 2D sub-scores, and 2D total score reflected potentially clinically-relevant differences in 3D variables with respect to the players' movement quality and risk of knee overloading (Figure 2). Therefore, the 2D scoring system here described represents a valid and comprehensive tool to identify the common risk factors for ACL injury in a user-friendly fashion.

In the frontal plane, poor Limb Stability 2D score was associated with higher Valgus Collapse (as described by Arundale et al. [19]), greater hip adduction, and greater hip internal rotation. Furthermore, hip frontal plane 3D kinematics was altered in the presence of poor Pelvis Stability and Trunk Stability 2D scores. Thus, poor frontal plane scores might reflect inadequate hip kinematics, hip abductor weakness, and a knee valgus tendency. Moreover, clusters of trials with low Limb Stability (0/2) and high Pelvis or Trunk Stability (2/2) or vice versa were found (Figure 3). Such clusters might indicate the presence of frontal plane compensatory strategies adopted by the players: the avoidance of knee valgus collapse was indeed compensated by a pelvic drop or trunk lateral tilt. Previous studies demonstrated that hip abductor weakness increases the risk of ACL injury by leading to increased lateral trunk displacement, pelvic drop, hip adduction, and knee valgus loads [23–25]. Perrot et al. [26] also found that poor lumbopelvic stability, assessed by clinical rating criteria of SLS, was associated with hip adduction, pelvic rotation, and trunk lateral tilt measured through 3D motion capture. Though in a purely subjective fashion, Crossley and colleagues [11] also correlated a "good" SLS performance with greater hip abduction and trunk lateral tilt strength as measured by a handheld dynamometer [11].

Several studies investigated the relationship between visual rating scales and 3D motion capture or 2D video-analysis: it was shown that athletes whose SLS performance was rated as "poor" exhibited greater hip adduction and greater mid-lateral knee joint center displacement in both 2D [7,27] and 3D [28,29] motion capture systems. Trunk- and core-based strengthening programs in prevention and rehabilitation have demonstrated a decreased risk of ACL injury [24,30,31]. The 2D scoring system described in the present study confirms the importance of a full-body assessment of the SLS task including the trunk-pelvis complex and suggests its involvement in the ACL injury risk mitigation.

Poor Movement Strategy 2D score (sagittal plane) was associated with stiff hip kinematics (lower hip flexion) and knee dominant movement strategy both in 3D kinematics and kinetics (Hip/Knee flexion angle and extensor moment ratio, respectively). Hip stiffness and knee dominant movement strategy (both kinematics and kinetics) were also strongly associated with a 2D total score ≤4/8. Previous studies demonstrated that the increased use of the knee extensors relative to the hip extensors should be considered as a risk factor for ACL injury and may contribute to various other knee injuries [4,25,32–34]. A deeper lower limb flexion was shown to predict a good SLS performance [25,35,36]. Since a decreased knee flexion has been associated to increased anterior cruciate ligament load [37], it has been suggested that sagittal plane body positions affect lower extremity biomechanics and the risk of knee injuries [38]. Paterno et al.[32] found that abnormal sagittal plane hip kinetics and postural stability deficits, are predictive of secondary ACL injury. Moreover, it has been demonstrated that participation in an ACL injury prevention training program decreased reliance on the knee extensor muscles and improved use of the hip extensor muscles [39]. Therefore, the ability for clinicians to effectively measure sagittal plane kinematics during functional tasks adds a valuable component to functional assessments and risk factor screenings. A high 2D total score could be indicative of an optimal or sub-optimal movement strategy and a limited risk of ACL injury. Thus, a high 2D total score could be used as a green light for the RTS clearance and provide a quick and effective feedback to the patient during the rehabilitation continuum.

In the present study, poor SLS were characterized by higher valgus collapse, hip stiffness, and knee dominant motor pattern. These findings are in line with previous literature [40] and demonstrate the importance of a total body assessment in the study of athletic performance and injury risk. Objective measures and an increased knowledge of such mechanisms might also contribute to maximizing the effectiveness of neuromuscular training programs aimed to reduce the ACL injury risk.

A strong correlation was also found between 2D and 3D kinematic variables, further confirming the concurrent validity of the 2D video-analysis system described in the present study. The FPKPA, e.g., showed a significant correlation with hip 3D frontal and transverse plane rotations and valgus collapse. In line with previous literature, the 2D assessment of the knee valgus mainly reflects hip internal rotation and adduction during the SLS task [41,42] . In this sense, the use of a "valgus collapse index" represents a comprehensive measure of lower limb valgus tendency and poor control [42,43]. Such neuromuscular factors can be targeted in neuromuscular training during RTS after an ACL injury. A good correlation was also observed for trunk tilt and pelvic tilt and rotation angles.

Previous studies investigated the reliability between 2D and 3D analyses in the frontal plane [16–18] and sagittal plane [18,33]. In the frontal plane, the two methodologies are frequently compared at the knee joint level only. The results of the present study partially agree with previous literature: a recent meta-analysis on the reliability and validity of frontal plane kinematics of the trunk and lower extremity measured with 2D cameras, revealed strong reliability of 2D analysis but no correlation between 2D knee frontal plane projection angle and 3D knee frontal plane angles ($r=0.13$, $p = 0.094$) for the SLS task [44]. In particular, Schurr et al. [18] reported poor agreement between the 2D video and 3D motion capture system for all frontal plane movements, such as trunk, hip, knee, and ankle, and no correlation between the two methods for the trunk, knee and ankle 2D frontal plane angles. Conflicting results were also found for 2D frontal plane hip angles, as Scholtes and Salsich [42] reported good to excellent relationship between 2D and 3D systems ($r = 0.82$, $p = 0.0001$) while Schurr et al. reported no relationship ($r = 0.15$, $p = 0.469$). In contrast, Herrington et al. [16] 2D knee valgus measures had a good correlation with knee abduction angle in 3D ($r = 0.79$, $p = 0.008$) and to knee abduction moment ($r = 0.65$, $p = 0.009$) too during SLS; and 2D hip adduction angle showed very good correlation with 3D hip adduction angle during SLS ($r = 0.81$, $p = 0.001$). Given the literature inconsistency, a reliable and valid methodology with proper intra- and inter-rater reliability and concurrent validity against the gold standard for both lower limb and trunk kinematics seems crucial to track a patient's RTS continuum from early to late-stage rehabilitation.

A strong correlation between our 2D and 3D angles of the hip and knee kinematics and kinetics was found also in the sagittal plane. In particular, hip/knee flexion angle and extensor moment ratios assessed through 3D motion capture showed the highest correlation with β/α ratio. Despite the different methodologies used, the agreement in sagittal plane kinematics and kinetics is a common finding in the previous literature [18,45,46]. This is not surprising, given the different ranges of motion between sagittal and frontal or transverse plane rotations in lower limb joints. However, a coupled frontal and sagittal plane assessment seems to remain the most complete methodology, given the multiplanar nature of the ACL injury mechanism [47].

The 2D scoring system proposed in the present study might be a simpler – but valid – alternative to standard 3D motion capture in the assessment of a common tasks as the SLS. Such a tool might help healthcare professionals identifying residual neuromuscular deficits and asymmetries after ACL reconstruction in a full-body multiplanar fashion. It can be used as part of multi-task assessment for large screenings aimed at identifying at-risk athletes in primary prevention. As a further strength, the quick and simple feedback contribute to promoting the patient's engagement and the self-correction during the rehabilitation process.

The present study has some limitations. First, the data were collected on healthy athletes during a single session. Therefore, it was not possible to provide the sensibility of the 2D scoring system in a test–retest condition after a preventative training program. Moreover, in order to test the validity of the scoring system while ensuring most of the variability, the data from 6 trials per subjects were considered separately, as commonly performed in biomechanical validation studies, instead of being averaged – potentially flattening the variability and generalizability of the results. Second, no strength measurements data (e.g., through dynamometers) were collected. Such data could have provided further valuable information towards injury risk assessment and corroborated the 2D scoring tool. The players' gender wasn't considering as a covariate. Third, the kinematical assessment was performed at the peak knee flexion angle, which was slightly different and impossible to standardize among the players. Lastly, no data were collected from ACL reconstructed patients. Further studies might investigate the minimum clinically-relevant side-to-side differences for the single 2D angles and scores.

5. Conclusion

The 2D video-analysis scoring system described in the present study was associated with kinematics and kinetics from gold standard 3D motion capture and might represent a valid tool to describe the movement quality of a SLS task. Such a tool can be used in RTS continuum to reliably identify neuromuscular deficits and risk factors for future ACL injury in a user-friendly fashion.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author contributions

All the authors read and approved the final version submitted, met the criteria for authorship as established by the International Committee of Medical Journals Editors, believe that the paper represents honest work, and can verify the validity of the results reported.

Ethics Information

The study was approved the *Blinded for Submission* (IRB approval: *Blinded for Submission*; ClinicalTrials.gov Identifier: *Blinded for Submission*).

Declaration of Interests

None.

Acknowledgments

The authors want to thank *Blinded for Submission* for the technical support in data acquisition.

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Tables

TABLE 1. Descriptive 2D and 3D biomechanics of Single-Leg Squat task

	Overall	Male	Female	p-value
2D biomechanics (video analysis)				
Frontal Plane Knee Projection Angle (°)	10.2 ± 14.7 [8.1 - 12.3]	12.7 ± 16.6 [9.4 – 16.0]	7.3 ± 11.7 [4.8 - 9.8]	0.012
Pelvic tilt Angle (°)	3.7 ± 4.1 [3.1 - 4.3]	4.1 ± 4.6 [3.2 – 5.0]	3.3 ± 3.5 [2.6 - 4.0]	n.s.
Trunk tilt Angle (°)	4.4 ± 4.1 [3.8 - 5.0]	4.9 ± 4.6 [4.0 - 5.8]	3.8 ± 3.4 [3.1 - 4.5]	n.s.
α (°)	87.8 ± 10.4 [86.3 - 89.3]	87.3 ± 11.5 [85.0 - 89.6]	88.4 ± 8.9 [86.5 - 90.3]	n.s.
β (°)	91.8 ± 12.3 [90.0 - 93.6]	94.7 ± 9.6 [92.8 - 96.6]	88.4 ± 14.1 [85.4 - 91.4]	0.001
β/α	1.0 ± 0.1 [1.0 – 1.0]	0.9 ± 0.1 [0.9 - 0.9]	1.0 ± 0.1 [1.0 – 1.0]	<0.001
3D biomechanics (motion capture)				
Knee varus-valgus (°)	17.3 ± 12.0 [15.5 - 19.1]	19.1 ± 12.8 [16.4 - 21.8]	15.2 ± 10.8 [12.8 - 17.6]	0.030
Knee intra-extra (°)	37.1 ± 9.4 [35.7 - 38.5]	34.2 ± 10.5 [32 - 36.4]	40.3 ± 6.8 [38.8 - 41.8]	<0.001
Knee flexion-extension (°)	85.9 ± 11.4 [84.2 - 87.6]	86.3 ± 12.4 [83.7 - 88.9]	85.3 ± 10.4 [83 - 87.6]	n.s.
Knee valgus collapse (°)	7.4 ± 9.0 [6.0 - 8.8]	8.3 ± 9.7 [6.3 - 10.3]	6.4 ± 8.1 [4.6 - 8.2]	n.s.
Knee extensor moment (N*m/BW)	-0.1 ± 0.1 [-0.1 - -0.1]	-0.1 ± 0.2 [-0.1 - -0.1]	-0.1 ± 0.1 [-0.1 - -0.1]	n.s.
Hip abd-adduction (°)	8.0 ± 6.4 [7.0 - 9.0]	7.2 ± 7.2 [5.7 - 8.7]	8.9 ± 5.2 [7.8 - 10.0]	n.s.
Hip intra-extra (°)	16.7 ± 12.8 [14.8 - 18.6]	20.2 ± 13.6 [17.4 – 23.0]	12.7 ± 10.7 [10.4 - 15.0]	<0.001
Hip flexion-extension (°)	54.2 ± 10.6 [52.6 - 55.8]	51.3 ± 11.2 [49.0 - 53.6]	57.4 ± 8.9 [55.5 - 59.3]	<0.001
Hip extensor moment (N*m/BW)	-0.3 ± 0.1 [-0.3 - -0.3]	-0.3 ± 0.1 [-0.3 - -0.3]	-0.4 ± 0.1 [-0.4 - -0.4]	<0.001
Hip/Knee flexion angle ratio	0.6 ± 0.1 [0.6 - 0.6]	0.6 ± 0.1 [0.6 - 0.6]	0.7 ± 0.1 [0.7 - 0.7]	<0.001
Hip/Knee extensor moment ratio	6.7 ± 3.3 [6.2 - 7.2]	5.3 ± 2.7 [4.7 - 5.9]	8.2 ± 3.1 [7.5 - 8.9]	<0.001
Pelvic lateral tilt (°)	-3.7 ± 4.1 [-4.3 - -3.1]	-4.5 ± 4.5 [-5.4 - -3.6]	-2.8 ± 3.3 [-3.5 - -2.1]	0.007
Pelvic rotation (°)	-3.1 ± 5.8 [-4 - -2.2]	-2.2 ± 6.5 [-3.6 - -0.8]	-4.0 ± 4.8 [-5.1 - -2.9]	0.045
Trunk lateral tilt (°)	-3.1 ± 5.4 [-3.9 - -2.3]	-3.9 ± 6.5 [-5.3 - -2.5]	-2.4 ± 3.6 [-3.2 - -1.6]	n.s.
Trunk rotation (°)	-1.7 ± 5.5 [-2.5 - -0.9]	-1.6 ± 5.9 [-2.8 - -0.4]	-1.7 ± 3.2 [-2.4 - -1.0]	n.s.

Abbreviations: α, supplementary of 2D knee flexion angle; β, supplementary of 2D hip flexion angle; n.s., non-significant difference.

TABLE 2. Frontal and transverse plane 3D biomechanics according to the frontal plane 2D scores

	Limb Stability					Pelvis Stability					Trunk Stability				
3D motion capture	**0 (n=29)**	**1 (n=53)**	**2 (n=87)**	**η_p^2**	**p-value**	**0 (n=10)**	**1 (n=48)**	**2 (n=111)**	**η_p^2**	**p-value**	**0 (n=19)**	**1 (n=51)**	**2 (n=99)**	**η_p^2**	**p-value**
Knee, varus-valgus (°)	18.9 ± 10.3	16.9 ± 12.8	16.9 ± 12.1	0.00	n.s.	14.1 ± 9.6	17.7 ± 9.9	17.4 ± 13.0	0.00	n.s.	21.0 ± 11.0	17.6 ± 12.1	16.3 ± 12.1	0.01	n.s.
Knee, intra-extra (°)	36.0 ± 12.1	35.3 ± 7.8	38.5 ± 9.2	0.02	n.s.	40.8 ± 12.2	37.9 ± 8.3	36.4 ± 9.6	0.02	n.s.	38.0 ± 6.9	35.65 ± 9.5	37.6 ± 9.8	0.01	n.s.
Hip, abd-adduction (°)	9.9 ± 3.6	11.0 ± 5.2	5.6 ± 6.7	0.16	<0.001	0.4 ± 7.6	7.7 ± 7.0	8.8 ± 5.5	0.10	<0.001	2.6 ± 6.7	7.2 ± 6.9	9.45 ± 5.3	0.12	<0.001
Hip, intra-extra (°)	21.4 ± 10.9	18.0 ± 12.6	14.3 ± 13.1	0.05	0.022	19.6 ± 12.5	18.0 ± 9.4	15.8 ± 14.1	0.01	n.s.	22.1 ± 13.9	17.10 ± 11.5	15.4 ± 13.1	0.03	n.s.
Valgus Collapse (°)	12.3 ± 6.0	12.2 ± 7.0	2.9 ± 8.5	0.27	<0.001	5.9 ± 4.5	8.0 ± 10.0	7.3 ± 8.8	0.00	n.s.	3.7 ± 7.3	6.7 ± 9.7	8.5 ± 8.7	0.03	n.s.

Abbreviations: n.s., non-significant difference.

TABLE 3. Sagittal plane 3D biomechanics according to the sagittal plane 2D scores

3D Motion capture	Movement Strategy 0 (n=44)	1 (n=75)	2 (n=50)	η_p^2	p-value
Knee, flexion-extension (°)	88.7 ± 13.1	86.1 ± 11.6	83.0 ± 8.9	0.04	n.s.
Hip, flexion-extension (°)	47.0 ± 7.7	52.3 ± 8.8	63.4 ± 8.8	0.36	<0.001
Hip/Knee flexion angle ratio	0.5 ± 0.1	0.6 ± 0.1	0.8 ± 0.1	0.39	<0.001
Knee extensor moment (N*m/BW)	-0.1 ± 0.1	-0.1 ± 0.2	-0.1 ± 0.1	0.01	n.s.
Hip extensor moment (N*m/BW)	-0.3 ± 0.1	-0.3 ± 0.1	-0.4 ± 0.1	0.08	0.001
Hip/Knee extensor moment ratio	5.3 ± 2.5	6.2 ± 3.0	8.6 ± 3.3	0.16	<0.001

Abbreviations: BW, Body Weight; n.s., non-significant difference.

TABLE 4. 2D vs 3D correlations

2D angle	3D angle	r	p-value
FPKPA (°)	Knee, varus-valgus (°)	0.05	n.s.
	Knee, intra-extra (°)	-0.13	n.s.
	Hip, abd-adduction (°)	0.35	<0.001
	Hip, intra-extra (°)	0.21	0.006
	Valgus Collapse (°)	0.48	<0.001
PA (°)	Pelvic lateral tilt (°)	-0.67**	<0.001
	Pelvic rotation (°)	0.18*	0.019
TA (°)	Trunk lateral tilt (°)	-0.51*	<0.001
	Trunk rotation (°)	0.06	n.s.
α (°)	Knee, flexion-extension (°)	-0.89**	<0.001
	Hip/Knee extensor moment ratio	0.15*	0.049
β (°)	Hip, flexion-extension (°)	-0.49**	<0.001
	Hip/Knee extensor moment ratio	-0.24	0.002
β/α	Hip/Knee flexion angle ratio	0.59**	<0.001
	Hip/Knee extensor moment ratio	0.39**	<0.001

Abbreviations: FPKPA, Frontal Plane Knee Projection Angle; PA, Pelvis Angle; TA, Trunk Angle; α, supplementary of 2D knee flexion angle; β, supplementary of 2D hip flexion angle; n.s., non-significant difference.

Figure legends

Figure 1. Description of 2D angles collected on sagittal (left) and frontal (right) view. The 2D angles are evaluated at the maximum knee flexion angle and are used to compute the 2D scoring system. The detailed description of the scoring system is given elsewhere [20].

Abbreviations: KFA=knee flexion angle; HKA=hip-trunk flexion angle.

Figure 2. 2D Total score correlation with 3D kinematic (knee valgus collapse[19] and kinetic (hip/knee extensor moment ratio) variables.

Figure 3. Heatmap chart of 2D Limb Stability (LS), Pelvis Stability (PS), and Trunk Stability (TS) sub-criteria. Each cell represents the count of the crossed scores for two criteria at a time. The heatmap allows to visualize possible compensations between frontal plane sub-criteria, e.g., the presence of trials with high LS and low TS.

Figure 4. Example of single-leg squat performed adequately (top row, total score 8/8) and non-adequately (bottom row, total score 2/8). The sub-scores and total score are reported on the right for both subjects.