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Original Research

Test-retest reliability and minimum detectable change for various frontal plane projection angles during dynamic tasks

D.M. Werner [a, *], S. Di Stasi [b, c], C.L. Lewis [d], J.A. Barrios [a]

[a] Department of Physical Therapy, University of Dayton, 300 College Park, USA
[b] Division of Physical Therapy, School of Health and Rehabilitation Sciences, The Ohio State University, 453 W 10th Avenue, Atwell Hall, Columbus, OH, USA
[c] Sports Medicine Research Institute, The Ohio State University Wexner Medical Center, USA
[d] Associate Professor of Physical Therapy, Rehabilitation Sciences and Medicine, Boston University, 635 Commonwealth Avenue, Boston, MA, USA

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A B S T R A C T

Objective: Establish between-day test-retest reliability metrics for 2-dimensional frontal plane projection angles (FPPAs) during the lateral step-down (LSD), single-limb squat (SLS), single-limb landing (SLL), and drop vertical jump (DVJ).
Design: Test-retest reliability study.
Setting: University laboratory.
Participants: 20 healthy adults (12 female, age = 23.60 ± 1.93 years old, body mass index = 24.26 ± 2.54 kg/m^2) were tested on 2 separate occasions 7–14 days apart.
Main outcome measures: Intraclass correlation coefficients (ICC), standard errors of the measurement (SEM), and minimal detectable change (MDC) values across the LSD, SLS, SLL, and DVJ for the following body region variables: trunk, trunk on pelvis, pelvis, hip, thigh to vertical, knee, and shank to vertical.
Results: There was moderate-to-substantial between-day test-retest reliability for nearly all body regions across all tasks (ICC = 0.65–0.96). SEM values varied across body regions and tasks (0.9–3.5°). MDCs were variable (2.3–9.8°). Of the body regions, MDCs were largest for the knee and hip. By task, MDCs were lowest for the LSD.
Conclusions: This study identified between-day test-retest reliability metrics for 2-dimensional FPPAs across a variety of body regions during commonly assessed clinical tasks. These data allow clinicians and researchers to more confidently assess true change between assessments or over time.

1. Introduction

Aberrant lower extremity and trunk movement patterns are often observed in those with or at risk for musculoskeletal pathology. These pathologies include anterior cruciate ligament (ACL) injuries (Hewett et al., 2005), patellofemoral pain (PFP) (Willson & Davis, 2008), femoroacetabular impingement syndrome (FAIS) (Lewis, Loverro, & Khuu, 2018) and acetabular labral injuries (Austin, Souza, Meyer, & Powers, 2008). In regards to knee and hip movement patterns, the presence of excessive dynamic lower extremity valgus is generally considered relevant to injury risk and important to address in management (Hewett, Myer, & Ford, 2006). Dynamic valgus can be considered a lower limb movement pattern characterized by kinematic knee abduction and external rotation concomitant with hip adduction and internal rotation, often in some higher-than-normal combinations (Scholtes & Salsich, 2017). Proximally, increased lateral trunk lean has been observed in still images during non-contact ACL injuries (Hewett, Torg, & Boden, 2009), and appears to differ in those with PFP during squatting (Nakagawa, Moriya, Maciel, & Serrao, 2012). Distally, excessive ankle eversion is also often noted. Efforts to correct or reduce dynamic lower extremity valgus in at-risk or injured populations are increasingly prevalent in the literature. These intervention approaches include neuromuscular training (Ford et al., 2015), feedback-based movement modification paradigms (Willy, Scholz, & Davis, 2012), and taping techniques (Rajasekar, Kumar, Patel, Ramprasad, & Samuel, 2018).

The kinematics that characterize patterns such as dynamic valgus are best assessed using three-dimensional (3D) motion

* Corresponding author.
E-mail addresses: Wernerd1@udayton.edu (D.M. Werner), stephanie.distasi@osumc.edu (S. Di Stasi), lewisc@bu.edu (C.L. Lewis), Jbarrios1@udayton.edu (J.A. Barrios).

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capture methods (Myer, Ford, Khoury, Succop, & Hewett, 2010). However, as clinical environments generally lack such resources, two-dimensional (2D) frontal plane video analysis has become an accepted surrogate approach. Recent findings from prospective 2D movement studies have identified frontal plane parameters from multiple body regions as potential risk factors for knee injuries (Dingenen et al., 2015; Numata et al., 2018). The seminal example of frontal plane video analysis is the frontal plane projection angle (FPPA) of the knee (Willson & Davis, 2008), derived by measuring the angle of intersection of the thigh and lower leg segments from a frontal view. This approach was originally established specifically for the knee joint during single-limb squatting using correlation to 3D joint kinematics as validation. However, FPPA assessments are now being applied to other body regions and for different movement tasks (Almeida et al., 2016; Dingenen, Barton, Janssen, Benoit, & Malliaras, 2018; Schurr, Marshall, Resch, & Saliba, 2017).

The increasing use of FPPA analyses stem partly from literature suggesting 2D methods have acceptable reliability, which can be influenced by variability from the rater, the task performance, and the measurement tool. Most previous reliability studies have been limited to some form of rater or within-session reliability of the knee joint FPPA during a single task (Lopes et al., 2018). These reliability outcomes do not directly apply to prospective and intervention research designs that require testing to occur over multiple sessions. For these purposes, between-day, test-retest reliability studies are needed to appropriately define minimum detectable change (MDC) thresholds, the magnitude of difference required between separate measures that is needed to be considered a real change (Weir, 2005).

The clinical value of 2D testing of functional lower extremity tasks is currently limited by the lack of test-retest reliability data. Previous studies have also focused almost exclusively on the knee joint, further limiting the utility of these findings (Gwynne & Curran, 2014; Herrington, Alenezi, Alzhrani, Alrayani, & Jones, 2017; Hughes et al., 2019; Miller & Callister, 2009; Munro, Herrington, & Carolan, 2012; Myer et al., 2014a; Tate, True, Dale, & Baker, 2015). As 2D assessment of movement becomes more commonplace, establishing test-retest reliability and MDC thresholds for FPPAs in body regions beyond the knee becomes necessary. Reliability data for these other body regions are largely absent in the literature for movement tasks relevant to those with PFP (Piva et al., 2006; Willson & Davis, 2008), FAIS (Harris-Hayes et al., 2016), and ACL injury (Myer et al., 2014b). To this end, investigation of lateral step-downs (LSD), single-limb squats (SLS), single-limb landings (SLL), and drop vertical jumps (DVJ) is warranted. Therefore, the purpose of this study was to establish between-day, test-retest reliability and MDC metrics for the trunk, pelvis, and lower extremity across these tasks.

2. Methods

2.1. Participants

Twenty healthy adults provided written informed consent as approved by the university's Institutional Review Board for participation in this study. Participants were included if they were 18–55 years old and reported an activity level of at least 5/10 on the Tegner Activity Scale (Briggs, Steadman, Hay, & Hines, 2009), meaning they ran at least 2 times per week. Participants were excluded if they presented with any history of lower extremity or spinal surgery, or injury within the last 12 months. The dominant limb, determined as the preferred limb to kick a ball, was the limb of interest. Test-retest sessions occurred 7–14 days apart to minimize any potential carry-over effects.

2.2. Two-dimensional video capture

Two-dimensional video data were collected at approximately 30 frames per second using a tripod-mounted and leveled smartphone camera (Motorola Droid Turbo Maxx 2, Lenovo, USA) placed 3 m anterior to the participant and 31 inches from the floor (Tate et al., 2015). To prepare participants for collection, circular markers were placed over the bilateral talar domes, mid-patellae, anterior superior iliac spines (ASIS), mid-thighs (the midpoints of the lines between the mid-patellae and ASIS markers), and the sternum.

2.3. Tasks

Participants performed the LSD, SLS, SLL, and DVJ tasks (Fig. 1). Task order was randomized and each task was verbally described and physically demonstrated by the examiner. Participants were allowed to familiarize themselves with each task prior to testing. Rest breaks of at least 2 min between tasks and at least 30 s between trials were implemented. For each task, 5 repetitions were captured. No fewer than 3 repetitions were analyzed per task during post-processing if trials were discarded due to quality control considerations.

The LSD was performed as previously described (Mostaed, Werner, & Barrios, 2018). Briefly, participants stood with hands on hips and on their test limb in full knee extension atop a 6-inch box with the contralateral limb hanging off the side of the box. They were then instructed to bend the test limb and tap their contralateral heel to the floor, and then return to the starting position at a self-selected pace. They were required to perform 6 continuous repetitions without losing balance.

For the SLS (Khuu, Foch, & Lewis, 2016) participants stood on their test limb with their contralateral knee flexed to 90°, the contralateral hip in neutral extension, and arms across chest. Participants then performed a single-limb squat in rhythm with a metronome set to 60 beats per minute, matching 1 beat for descent and 1 beat for ascent (Lewis, Foch, Luko, Loverro, & Khuu, 2015). A trial was deemed successful if speed was matched to the metronome and balance was maintained.

For the SLL (Pozzi, Di Stasi, Zeni, & Barrios, 2017), participants stood with hands on hips atop a 30-cm box on their test limb with their contralateral knee flexed to 90°. They were instructed to drop, while focusing on not jumping, off the box and land on the test limb. A trial was deemed successful if single-limb stance was maintained for 3 s upon landing.

To perform the DVJ (Myer et al., 2014b), participants stood with bilateral lower extremity support atop a 30-cm box. They then dropped off the box, landed with both feet, and immediately performed a maximal countermovement jump reaching with both hands for an overhead target. Participants were asked to land with both feet simultaneously during the landing phase and reach with both hands overhead during the jumping phase for a successful trial, with the first landing phase analyzed.

2.4. Data processing

FPPA data were generated by a single board-certified orthopedic physical therapist using Kinovea software (Kinovea 0.8.15, http://www.kinovea.org). Angles were extracted at the frame when the test limb's ipsilateral ASIS was at its lowest point. Based on videos acquired during pilot testing, it was observed that the ASIS marker drop-out would occur in some instances. As a potential surrogate, the sternum marker was identified as an alternate trajectory. To evaluate this approach, the frame number differential between the low points of the ipsilateral ASIS and the sternum markers was assessed across all participants and across all tasks.

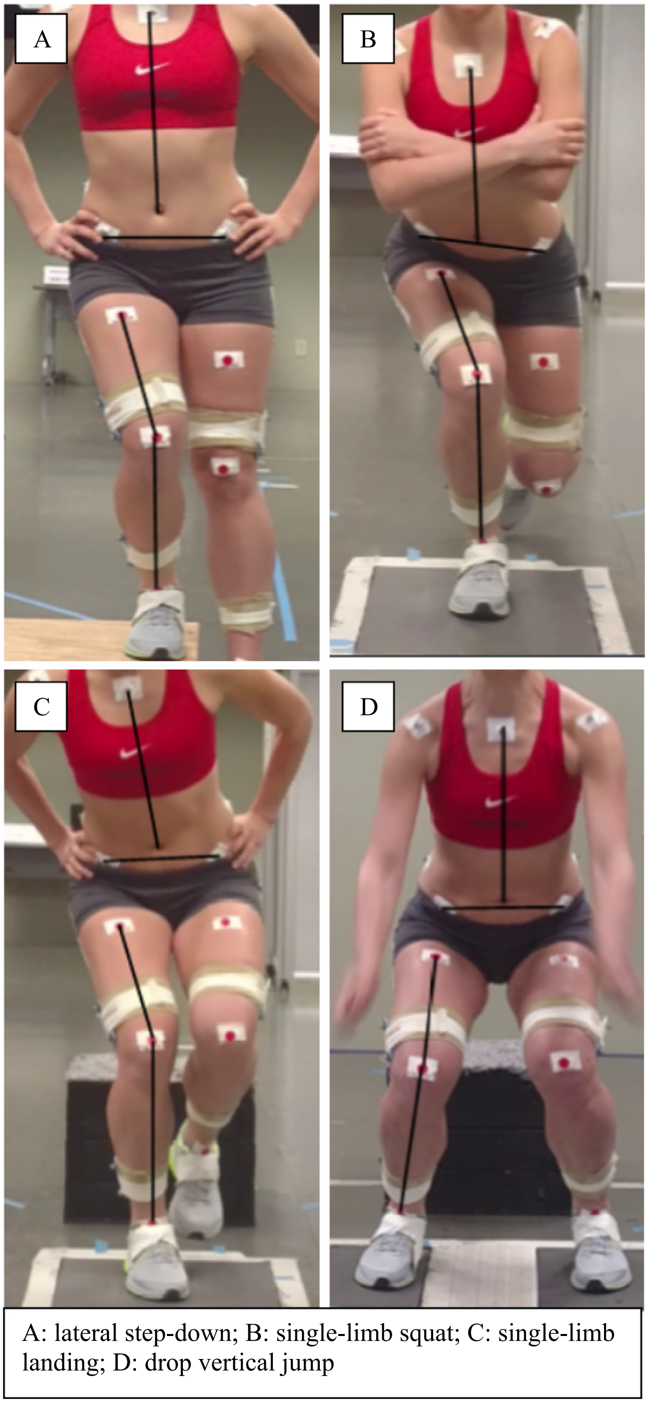


Fig. 1. Sample lines drawn at extraction frame for assessment of frontal plane projection angles (FPPAs).

Per previous literature, the FPPA for the knee (FPPAk) was generated as the angle of intersection between a line from the mid-thigh marker to the mid-patellar marker and a line from the mid-patellar marker to the talar dome marker, with positive values denoting knee adduction (Munro et al., 2012; Willson & Davis, 2008). The remaining FPPAs were generated as follows (Fig. 2). The FPPA for the shank (FPPAsh) was generated with a line from the mid-patella to the talar dome, referenced to vertical, with positive values denoting shank adduction. The FPPA for the thigh (FPPAth) was generated with a line from the mid-thigh to patella, referenced to vertical, with positive values noting thigh adduction. The FPPA for the hip (FPPAh) was generated as the angle of intersection between a line from the mid-thigh to the patella and a line from the ipsilateral ASIS to the contralateral ASIS, with positive values noting hip adduction. The FPPA for the pelvis (FPPAp) was generated with a line from the ipsilateral ASIS to the contralateral ASIS, referenced to horizontal, with positive values denoting contralateral pelvic drop. The FPPA for the trunk (FPPAt) was generated with a line from the sternum to the naval, referenced to vertical, with positive values denoting ipsilateral trunk lean. Lastly, the FPPA for the trunk on the pelvis (FPPAtp) was generated with the line from sternum to naval and a line from the ipsilateral ASIS to the contralateral ASIS, with positive values denoting trunk lean away from contralateral aspect of pelvis.

2.5. *Statistical analysis*

Descriptive and statistical analyses were performed using SPSS 24.0 (IBM Corp., Armonk, NY, USA). Mean values and standard deviations for each FPPA measure were generated from both testing sessions. Between session difference testing of means and standard deviations was conducted using paired t-tests (alpha = 0.05). For the test-retest reliability analyses, intraclass correlation coefficients ([ICC] model 3,k) were calculated, and deemed moderate at the 0.6 level and substantial at the 0.8 level (Shrout, 1998). Standard errors of the measure (SEM) and minimal detectable change (MDC) thresholds using a 95% confidence interval were then generated (Stratford & Goldsmith, 1997) using the following equations:

Standard error of the measurement = standard deviation x $\sqrt{(1 - \text{ICC})}$

Minimum detectable change = SEM x 1.96 x $\sqrt{2}$

3. Results

3.1. *Participants*

Descriptive data for participants is presented in Table 1. A greater proportion of females (60%) participated in the study, with a normal BMI and an activity level of 5/10 on the Tegner Scale. All but one participant was right-leg dominant.

3.2. *Event detection using surrogate marker*

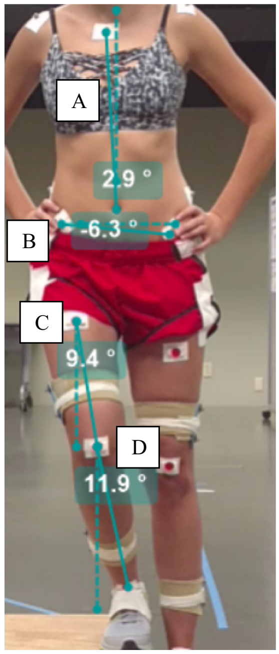
To assess the sternum marker as a potential surrogate for the ipsilateral ASIS marker, all trials where both markers were visible were analyzed. The frame number difference for when each marker reached its lowest identifiable point was recorded to assess raw frame error. Approximately 9% (68/730) of trials necessitated use of the sternum as a surrogate marker for event detection. In those instances, angles were only generated from visible markers at the extraction frame.

3.3. *Between-day difference testing*

Means from both testing sessions are provided in Table 2. Across tasks, 25/28 parameters did not differ between testing sessions. During the SLL, FPPAt, FPPAp, and FPPAsh differed.

3.4. *Inter-trial standard deviations*

Additionally, inter-trial standard deviations for each session are provided in Table 3. No differences were observed.



A: Frontal plane projection angle trunk to vertical; B: Frontal plane projection angle pelvis to horizontal; C: Frontal plane projection angle thigh to vertical; D: Frontal plane projection angle shank to vertical

Fig. 2. Raw examples of frontal plane projection angle estimates.

Table 1
Descriptive participant data.

	Mean (standard deviation)	Frequency
Sex Frequency (F:M)		12:8
Leg Dominance (R:L)		19:1
Age (years)	23.60 ± 1.93	
BMI (kg/m^2)	24.26 ± 2.54	
Tegner Activity Scale	5.65 ± 0.88	

Abbreviations: F - female; M - male; BMI - body mass index; kg - kilograms; m - meters; R - right; L - left.

3.5. Reliability analyses

Between-day test-retest reliability data for all FPPA variables across all tasks are presented in Table 4. For the LSD, all FPPA measures (7/7) yielded a reliability coefficient above 0.80, and MDCs ranged from approximately 3-8°. For the SLS, 6/7 FPPA reliability coefficients were above 0.80, with MDCs that ranged from approximately 3.5–10°. For the SLL, 5/7 were above 0.80, with MDCs that ranged from approximately 5-9°. Lastly, for the DVJ, 6/7 coefficients were at or above 0.80, with MDCs that ranged from 2 to 8°.

With regards to specific FPPA variables across tasks, FPPAk yielded a reliability coefficient greater than or equal to 0.80 on all tasks (4/4), and MDCs ranged from approximately 8-10°. For FPPAtp and FPPAt, 3/4 tasks demonstrated reliability coefficients greater than or equal to 0.80 with MDCs that ranged from approximately 3-6°. For FPPAp, FPPAth, and FPPAh, 4/4 tasks demonstrated reliability coefficients greater than or equal to 0.80, with MDCs that ranged from approximately 2-8°. For FPPAsh, 2/4 tasks demonstrated reliability coefficients greater than or equal to 0.80, with MDCs that ranged from approximately 4-6°.

4. Discussion

The main purpose of this study was to assess the between-day test-retest reliability of various FPPAs throughout the trunk and lower extremities during 4 common laboratory tasks, and to derive MDC thresholds for each parameter. Two slower grounded tasks and 2 faster landing tasks were evaluated. Generally, moderate-substantial test-retest reliability was observed, depending on the FPPA measure and the task.

The task with the most reliable FPPAs across body regions was the LSD. Distinctly, this was the lone task constrained by fixed depth, as all subjects utilized a standardized box height. Further, the LSD was the only task with an external mechanosensory input, due to contralateral heel contact with the floor. These factors may have contributed to the high reliability. To our knowledge, this is the only study to have evaluated the reliability of any FPPAs during the LSD task. The largest MDC thresholds were seen for the FPPAk, showing that 7–8 degrees of change in 2D knee varus-valgus between testing sessions would be required to be considered a true difference. In the 2D reliability literature regarding the LSD, a categorical quality of movement scale has been previously found to be moderately reliable between raters in patients with patellofemoral pain, but test-retest data were not collected (Piva et al., 2006). This quality of movement score can range from 0 to 6, with higher scores indicative of more movement faults. The relationships and unique information gained from these assessments is unknown. In comparison to the FPPA data from the other tasks, the LSD produced the lowest MDC thresholds and should be considered as an evaluative task in test-retest scenarios.

The SLS had generally moderate-substantial reliability for most FPPAs. The between-day test-retest reliability of 2D FPPAs of the SLS have been examined previously (Table 5), however most studies have investigated only FPPAk (Munro et al., 2012; Tate et al.,

Table 2
FPPA values across tasks and days in degrees (expressed using mean (standard deviation) format).

	Lateral Step-Down		
	Day 1	Day 2	*p*-value
FPPAk	−5.1 (7.6)	−6.5 (7.3)	0.236
FPPAtp	5.3 (4.3)	5.3 (3.9)	0.974
FPPAt	3.0 (2.9)	3.2 (3.2)	0.669
FPPAp	2.3 (3.6)	2.1 (3.1)	0.758
FPPAth	11.4 (4.3)	11.8 (4.1)	0.590
FPPAh	13.7 (6.2)	13.8 (5.8)	0.861
FPPAsh	6.4 (4.0)	5.2 (4.3)	0.156
	Single-Limb Squat		
	Day 1	Day 2	*p*-value
FPPAk	−4.1 (8.6)	−3.8 (9.1)	0.830
FPPAtp	11.4 (6.0)	10.2 (6.2)	0.267
FPPAt	5.2 (5.3)	5.2 (4.9)	0.742
FPPAp	6.7 (4.5)	5.6 (5.3)	0.065
FPPAth	11.4 (5.5)	11.3 (5.3)	0.891
FPPAh	18.6 (7.9)	17.2 (8.6)	0.096
FPPAsh	7.3 (3.9)	7.5 (4.6)	0.832
	Single-Limb Landing		
	Day 1	Day 2	*p*-value
FPPAk	−7.5 (7.6)	−5.5 (8.1)	0.181
FPPAtp	6.8 (3.8)	7.8 (3.0)	0.222
FPPAt	9.6 (5.3)	13.1 (5.6)	<0.001
FPPAp	−2.8 (4.4)	−5.4 (4.7)	0.004
FPPAth	12.2 (4.9)	10.8 (5.1)	0.144
FPPAh	9.4 (7.6)	5.3 (8.2)	0.007
FPPAsh	4.7 (3.2)	5.0 (3.9)	0.713
	Drop Vertical Jump		
	Day 1	Day 2	*p*-value
FPPAk	12.6 (16.0)	10.5 (14.5)	0.120
FPPAtp	0.1 (2.9)	0.2 (2.7)	0.910
FPPAt	1.6 (3.2)	1.1 (2.7)	0.418
FPPAp	−0.9 (2.0)	−0.9 (1.8)	0.966
FPPAth	−14.4 (9.9)	−13.5 (8.4)	0.408
FPPAh	−13.2 (8.2)	−12.5 (8.0)	0.879
FPPAsh	−1.8 (7.3)	−3.0 (7.2)	0.064

Angle description: FPPAk - positive values denote knee adduction; FPPAtp - positive values denote trunk lean away from contralateral aspect of pelvis; FPPAt - positive values denote ipsilateral trunk lean; FPPAp - positive values denote contralateral pelvic drop; FPPAth - positive values denote thigh adduction; FPPAh - positive values denote hip adduction; FPPAsh - positive values denote shank adduction.

Table 3
Inter-trial variability per day.

	Lateral Step-Down		
	Day 1 Standard Deviation	Day 2 Standard Deviation	*p*-value
FPPAk	2.46	2.67	0.452
FPPAtp	1.79	1.65	0.598
FPPAt	1.56	1.46	0.697
FPPAp	1.44	1.39	0.813
FPPAth	1.21	1.32	0.408
FPPAh	2.24	2.20	0.871
FPPAsh	1.65	1.73	0.605
	Single-Limb Landing		
	Day 1 Standard Deviation	Day 2 Standard Deviation	*p*-value
FPPAk	4.69	4.91	0.650
FPPAtp	2.28	1.91	0.226
FPPAt	1.82	1.66	0.588
FPPAp	1.79	1.54	0.335
FPPAth	2.33	2.36	0.922
FPPAh	2.60	2.56	0.722
FPPAsh	2.55	2.79	0.476
	Single-Limb Landing		
	Day 1 Standard Deviation	Day 2 Standard Deviation	*p*-value
FPPAk	4.05	4.11	0.934
FPPAtp	3.86	2.60	0.234
FPPAt	3.10	2.97	0.802
FPPAp	3.16	2.36	0.170
FPPAth	2.02	2.50	0.131
FPPAh	3.78	3.84	0.915
FPPAsh	2.34	1.89	0.362
	Drop Vertical Jump		
	Day 1 Standard Deviation	Day 2 Standard Deviation	*p*-value
FPPAk	5.32	5.22	0.906
FPPAtp	1.52	1.58	0.830
FPPAt	1.68	1.57	0.672
FPPAp	0.98	1.04	0.719
FPPAth	3.77	3.30	0.326
FPPAh	3.54	3.31	0.624
FPPAsh	2.43	2.50	0.886

Abbreviations: SD - standard deviation; FPPAk - frontal plane projection angle of the knee; FPPAh - frontal plane projection angle of the hip; FPPAt - frontal plane projection angle of the trunk; FPPAp - frontal plane projection angle of the pelvis; FPPAtp - frontal plane projection angle of the trunk on pelvis; FPPAth - frontal plane projection angle of the thigh; FPPAsh - frontal plane projection angle of the shank; * - statistically significant.

2015; Gwynne & Curran, 2014). One study examined both FPPAk and FPPAh (Herrington et al., 2017), while another examined FPPAk and FPPAsh (Hughes et al., 2019). The reliability results of the current study are in line with previous research investigating FPPAs of the knee, hip and shank (Tables 4 and 5). The FPPAk MDC values reported or otherwise calculated have been widely variable, with lower estimates in the range of 4–5° (Tate et al., 2015) and higher estimates over 15° (Hughes et al., 2019). In regards to the knee, the MDC values are most similar to those reported by Munro and colleagues (Munro et al., 2012). The current MDC values for FPPAh are comparable to those generated from data presented by Herrington et al. (Herrington et al., 2017). Likewise, the MDC values for FPPAsh are similar to those previously reported (Hughes et al., 2019). It should be noted that as SLS mechanics vary based on the position of the non-weight bearing limb (Khuu et al., 2016), methodological differences between studies likely contributed to the observed variability in MDC estimates. The reliability of a unique 2D FPPA application for the SLS, the dynamic valgus index, has also been studied. This metric essentially sums FPPAk and FPPAh and has been found to be moderately reliable within and between raters, but test-retest data were not gathered (Scholtes & Salsich, 2017). Despite inconsistencies in the reliability literature, the SLS is a viable task for test-retest applications using the FPPAs from the current study.

The DVJ FPPAs demonstrated substantial reliability across 6/7 body regions. Two previous studies have investigated between-day test-retest reliability for the DVJ, both focusing on the FPPAk. In a sex comparison study, Munro et al. (Munro et al., 2012) reported reliability coefficients and MDC values comparable to the current study. Myer et al. (Myer et al., 2014a) reported lower reliability coefficients than the current study, but uniquely examined between-day reliability across three testing centers, which introduced examiner variation into the total variation. The DVJ has been found to be predictive of ACL injury risk (Hewett et al., 2005) and is commonly used in neuromuscular training efforts aimed at reducing ACL injury risk. It is therefore relevant to be aware of the magnitude of difference needed to determine true change in DVJ FPPAs.

All measures during the SLL demonstrated at least moderate reliability, with 5/7 measures substantially reliable. However, significant differences by testing session were seen for 3/7 parameters. Two prior studies have investigated the between-day test-retest

Table 4
Between-day test-retest ICCs, ICC 95% CIs, SEMs and MDCs for 2D FPPAs.

	ICC (3,*k*)	ICC 95% CI	SEM (degrees)	MDC (degrees)
	Lateral Step-Down			
FPPAk	0.86	0.64–.94	2.8	7.8
FPPAtp	0.87	0.67–.95	1.5	4.1
FPPAt	0.89	0.72–.96	1.0	2.8
FPPAp	0.86	0.64–.94	1.3	3.5
FPPAth	0.88	0.70–.95	1.5	4.1
FPPAh	0.85	0.62–.94	2.3	6.5
FPPAsh	0.81	0.51–.92	1.8	5.1
	Single-Limb Squat			
	ICC (3,*k*)	**ICC 95% CI**	**SEM (degrees)**	**MDC (degrees)**
FPPAk	0.84	0.59–.94	3.5	9.8
FPPAtp	0.94	0.84–.98	1.5	4.0
FPPAt	0.90	0.74–.96	1.6	4.5
FPPAp	0.95	0.85–.98	1.3	3.5
FPPAth	0.87	0.68–.95	1.9	5.4
FPPAh	0.93	0.82–.97	2.2	6.0
FPPAsh	0.76	0.39–.90	2.1	5.8
	Single-Limb Landing			
	ICC (3,*k*)	**ICC 95% CI**	**SEM (degrees)**	**MDC (degrees)**
FPPAk	0.82	0.51–.94	3.3	9.2
FPPAtp	0.65	0.07–.87	2.0	5.5
FPPAt	0.89	0.69–.96	1.8	5.1
FPPAp	0.85	0.61–.95	1.7	4.8
FPPAth	0.84	0.56–.94	2.0	5.6
FPPAh	0.86	0.62–.95	3.0	8.3
FPPAsh	0.75	0.31–.91	1.8	4.9
	Drop Vertical Jump			
	ICC (3,*k*)	**ICC 95% CI**	**SEM (degrees)**	**MDC (degrees)**
FPPAk	0.96	0.91–.99	2.9	8.1
FPPAtp	0.80	0.46–.93	1.3	3.5
FPPAt	0.77	0.41–.91	1.4	4.0
FPPAp	0.80	0.43–.93	0.9	2.3
FPPAth	0.93	0.83–.97	2.4	6.5
FPPAh	0.94	0.83–.98	1.9	5.3
FPPAsh	0.96	0.91–.99	1.4	3.9

Abbreviations: SEM - standard error of measurement (degrees); MDC - minimal detectable change (degrees); ICC - intraclass correlation coefficient; CI - confidence interval; FPPAk - frontal plane projection angle of the knee; FPPAh - frontal plane projection angle of the hip; FPPAt - frontal plane projection angle of the trunk; FPPAp - frontal plane projection angle of the pelvis; FPPAtp - frontal plane projection angle of the trunk on pelvis; FPPAth - frontal plane projection angle of thigh; FPPAsh - frontal plane projection angle of shank.

reliability of FPPAk (Herrington et al., 2017; Munro et al., 2012) during the SLL, with Herrington and colleagues (Herrington et al., 2017) also evaluating FPPAh. The current study found comparable ICC values. However, we found larger SEM and MDC values for both variables than by Herrington et al. (Herrington et al., 2017). It should be noted that the MDC estimates for the study by Herrington and colleagues were not reported and therefore derived. Further, the SLL task procedures varied for each study. As the SLL task has been found to reveal differences in neuromuscular landing strategy after ACL reconstruction (Pozzi et al., 2017), the SLL should be considered for test-retest assessments when using the FPPAs from the current study.

Clinicians may also be interested in the reliability of specific FPPAs across tasks. Clinical interest in the use of FPPAk is high, due in part to multiple validation efforts for FPPAk involving correlation to 3D knee joint angles (Gwynne & Curran, 2014; Herrington et al., 2017; Sorenson, Kernozek, Willson, Ragan, & Hove, 2015; Willson & Davis, 2008). However, across the four tasks, the MDC estimates for FPPAk were the largest in magnitude. These data indicate that using FPPAk in test-retest scenarios requires scrutiny to the size of the difference to ensure change observed exceeds MDC values. FPPAh has also been reported in previous studies, and validated per very good correlation ($r = 0.81$) to 3D hip adduction angle (Herrington et al., 2017). In the current study, FPPAh demonstrated the second highest MDC estimates across most tasks despite generally high ICC values (0.85–0.94), suggesting higher between subject variability. Clinicians should take note of these data in that higher reliability coefficients do not necessarily imply lower MDC values.

The reliability of the remaining FPPAs reported in this study are either novel or scarcely described in the literature. However, it should be noted that most of these parameters had lower MDC values than FPPAk and FPPAh, which are more commonly reported. In regards to the trunk, while the validity of 2D trunk measures has been questioned during SLS (Lopes et al., 2018; Schurr et al., 2017), good reliability has been reported (Dingenen, Malfait, Vanrenterghem, Verschueren, & Staes, 2014). Inconsistent methodologies to derive trunk angles were noted. The reliability of a 2D thigh segment was reported by Miller and Callister (Miller & Callister, 2009). The between-day test-retest reliability of a thigh to horizontal measure was acceptable, however, the battery of tasks differed from the current study. During a SLS, Hughes et al. (Hughes et al., 2019) reported on a shank parameter to vertical and found comparable reliability to the current study. The relative paucity of this reliability literature is notable. Further, little has been done to validate these measures either as prospective injury risk factors or as related to 3D movement patterns. Given the clinical utility of 2D video measures, this area of research merits further work.

It should be appreciated that lower MDCs are not necessarily more readily exceeded due to a change in movement pattern. Factors such as available range of motion and task specificity may constrain movements in specific body regions. For example, FPPAp during the DVJ is unlikely to demonstrate large deviations from horizontal due to double limb support, even weight distribution, and limited available range of motion with any pelvic drop or rise. Further, when comparing FPPAp MDCs between the DVJ and SLL, less than half the amount of change in FPPAp would be needed during the DVJ (2.3°) to be considered beyond measurement error in comparison to during the SLL (4.8°).

There are limitations to this study. Despite the relative rigor of between-day test-retest designs, a single rater was used, limiting the ability to infer reliability across raters. However, for test-retest situations, utilization of a single rater is advised. A healthy study population was used, and it is possible that a clinical population might perform these tasks with more or less consistency. It is unknown to what extent these results are generalizable to other tasks, such as running or cutting activities, as well as other versions of the study tasks. Carry-over effects were possible between sessions, although we observed minimal changes in task variability between sessions based on the standard deviations (Table 3). Finally, it should be acknowledged that 2D assessment is prone to parallax error due to potential rotational variations in participants, and therefore cannot substitute for 3D methodologies.

5. Conclusion

The results of this study provide between-day test-retest reliability, SEM, and MDC values for FPPAs of the trunk, pelvis and lower extremity joints and segments during commonly performed dynamic tasks. These data allow clinicians and researchers to better identify true change in these variables in longitudinal or intervention situations.

Table 5
Reliability, standard error of measurement, and minimal detectable change values for 2-dimensional frontal plane measurements.

Study	Task	Variable	ICC Model	ICC	SEM	MDC
Miller & Callister, (2009)	Forward Step Up	FPPAk	r	0.75	NR	6.31
		Thigh to Horizontal	r	0.72	NR	4.24
	Single-Leg DVJ	FPPAk	r	0.64	NR	8.75
		Thigh to Horizontal	r	0.72	NR	4.15
Munro et al., (2012)	SLS (male)	FPPAk	3,1	0.88	2.75	7.63
	SLS (female)	FPPAk	3,1	0.72	3.22	8.93
	DVJ (male)	FPPAk	3,1	0.89	3.00	8.32
	DVJ (female)	FPPAk	3,1	0.91	3.01	8.34
	SLL (male)	FPPAk	3,1	0.80	2.72	7.54
	SLL (female)	FPPAk	3,1	0.82	2.85	7.90
Tate et al., (2015)	SLS expert	FPPAk	3,k	0.91	1.7	4.71*
	SLS novice	FPPAk	3,k	0.94	1.6	4.43*
Myer et al., 2014a)	DVJ	FPPAk - Left	2,1	0.64	NR	NR
		FPPAk - Right	2,1	0.80	NR	NR
Hughes et al., (2019)	SLS (preferred leg)	FPPAk	3,1	0.39	5.99	16.61
		FPPAsh	3,1	0.74	1.64	4.55
	SLS (non-preferred leg)	FPPAk	3,1	0.74	3.73	10.33
		FPPAsh	3,1	0.73	1.73	4.78
Gwynne & Curran, (2014)	SLS	FPPAk	2,1	0.74	3.82	10.58*
Herrington et al., (2017)	SLS	FPPAk	3,1	0.87	1.93	5.34*
		FPPAh	3,1	0.79	1.93	5.34*
	SLL	FPPAk	3,1	0.87	1.4	3.88*
		FPPAh	3,1	0.86	1.43	3.96*

Abbreviations: FPPAk - frontal plane projection angle of the knee; ICC - intraclass correlation coefficient; SEM - standard error of measurement (degrees); MDC - minimal detectable change (degrees); DVJ - drop vertical jump; SLS - single-limb squat; SLL - single-limb landing; NR - not reported; * - calculated from reported data.

Ethical statement

Ethical approval

This study was approved by the Institutional Review Board at the University of Dayton.

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Declaration of competing interest

There are no conflicts of interest declared for the author group.

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