©Journal of Sports Science and Medicine (2021) **20**, 759-765
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2021.759

**Research article**

# Comparison of Lower Extremity Kinematics during the Overhead Deep Squat by Functional Movement Screen Score

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## Abstract

It is unclear if the Functional Movement Screen (FMS) scoring criteria identify kinematics that have been associated with lower extremity injury risk. The purpose was to compare lower extremity kinematics of the overhead deep squat (OHDS) during the FMS between individuals who were grouped on FMS scoring. Forty-five adults who were free of injury and without knowledge of the FMS or its scoring criteria (males = 19, females = 26; height = 1.68 ± 0.08 m; mass = 70.7 ± 13.0 kg). Three-dimensional lower extremity kinematics during an OHDS were measured using a motion capture system. One-way MANOVA was used to compare kinematic outcomes (peak hip flexion angle, hip adduction angle, knee flexion angle, knee abduction angle, knee internal rotation angle, and ankle dorsiflexion angle) between FMS groups. Those who scored a 3 had greater peak hip flexion angle ($F_{2,42} = 8.75$; $p = 0.001$), knee flexion angle ($F_{2,42} = 13.53$; $p = 0.001$), knee internal rotation angle ($F_{2,42} = 12.91$; $p = 0.001$), and dorsiflexion angle ($F_{2,42} = 9.00$; $p = 0.001$) compared to those who scored a 2 or a 1. However, no differences were found in any outcome between those who scored a 2 and those who scored a 1, or in frontal plane hip or knee kinematics. FMS scoring for the OHDS identified differences in squat depth, which was characterized by larger peak hip, knee, and dorsi- flexion angles in those who scored a 3 compared with those who scored 2 or 1. However, no differences were found between those who scored a 2 or 1, and caution is recommended when interpreting these scores. Despite a different FMS score, few differences were observed in frontal or transverse plane hip and knee kinematics, and other tasks may be needed to assess frontal plane kinematics.

**Key words:** FMS, injury, biomechanics.

## Introduction

Various tests are used to identify movement patterns that may contribute to injury risk. For instance, the overhead deep squat (OHDS), and drop jump assess lower extremity movement and may identify biomechanical patterns that contribute to injury risk (Bulgan, 2017; Butler et al., 2010; Mauntel et al., 2015; Myer et al., 2014; Padua et al., 2009). The Functional Movement Screen (FMS) was developed to identify movement asymmetry and/or dysfunctional movement patterns of the upper and lower extremity and trunk (Butler et al., 2010; Cook et al., 2014; Dorrel et al., 2015; Kraus et al., 2015; Whiteside et al., 2014). The FMS is an aggregate of seven tests (OHDS, hurdle step, in-line lunge, shoulder mobility, active straight-leg raise, trunk stability push-up, and rotary stability), and each test is scored on a scale from 0 to 3 (Cook et al., 2014). A score of 3 indicates movement with no compensatory patterns, 2 indicates completion of movement with some compensation, 1 indicates an inability to complete the movement as prescribed, and 0 indicates pain with movement (Cook et al., 2014). Individual scores are commonly summed as composite, and a score of less than 14 has been used as a cutoff score to assess injury risk in athletes and tactical populations (Dorrel et al., 2015; Garrison et al., 2015; Mokha et al., 2016; Rusling et al., 2015).

Evidence is mixed regarding the composite FMS score to predict injury incidence (Dorrel et al., 2015; Garrison et al., 2015), which may suggest that the scoring criteria are not appropriate to evaluate the multifactorial nature of injury. Conversely, the FMS has been associated with performance characteristics such as maximal jumping height and sprinting speed (Lockie et al., 2015). Previous research indicates that interrater reliability and intersession reliability of FMS scoring is moderate to good (Garrison et al., 2015; Minick et al., 2010; Shultz et al., 2013). However, there is ambiguity for midrange FMS scores when assigning a score of 2 (Minick et al., 2010; Whiteside et al., 2014), and studies have struggled to identify measurable differences in movement patterns between scoring a 2 or 1 (Cook et al., 2014; Whiteside et al., 2014). As such, it is unclear if the FMS accurately measures biomechanical patterns when measured using motion capture (Butler et al., 2010; Rabin et al., 2016). Butler et al. observed progressively lower knee flexion angles during the OHDS in those who scored a 1 compared with a 2, and in those who scored a 2 compared with a 3 (Butler et al., 2010). However, hip flexion and ankle dorsiflexion angles were similar between those who scored a 2 and 3. Moreover, frontal and transverse plane kinematics were not assessed, and analyses were restricted to peak values rather than comprehensively throughout the OHDS. Overall, studies are needed that comprehensively evaluate biomechanical patterns of the OHDS based on FMS scoring categories, which may clarify why the FMS does not consistently predict injury incidence, and aid in improving FMS scoring guidelines.

The OHDS is a test of mobility and stability of multiple joints for performance, and contributes the largest proportion of variance to the composite FMS score (Butler et al., 2010; Cook et al., 2014; Kraus et al., 2015; Minick et al., 2010). Limited sagittal plane hip and knee mobility contribute to reduced hip or knee flexion during an OHDS and a lower FMS score (Bulgan, 2017; Butler et al., 2010;

Received: 17 July 2021 / Accepted: 15 September 2021 / Published (online): 01 October 2021

Janicki et al., 2017; Mauntel et al., 2015). Similarly, restricted ankle dorsiflexion may be associated with less squat depth (Butler et al., 2010; Cook et al., 2014; Janicki et al., 2017). The scoring criteria of the OHDS during the FMS also considers knee alignment relative to the feet in the frontal plane (Butler et al., 2010; Cook et al., 2014). Previous research has utilized the OHDS to measure dynamic knee valgus (Mauntel et al., 2015), which could be useful given the contribution of valgus to ACL injury in other tasks such as landing or cutting (Hewett et al., 2005). However, dynamic knee valgus has contributions from multiple joints, and also includes hip adduction, hip internal rotation, knee abduction, and knee external rotation (Hewett et al., 2005). Subtle compensatory knee and hip movements in the frontal and transverse plane may be difficult to visually identify throughout the entire OHDS during the FMS, and studies are needed to determine if the FMS adequately quantifies frontal and transverse plane hip and knee motions.

The purpose of this study was to compare hip, knee, and ankle kinematics during the OHDS between scoring categories (3, 2, or 1) of the FMS. It was hypothesized that those who scored a 3 would have greater peak hip and knee flexion and ankle dorsiflexion angles, and smaller peak hip adduction, knee abduction and external rotation angles compared to those who scored a 2 or 1. Similarly, we hypothesized that those who scored a 2 would have greater peak hip and knee flexion and ankle dorsiflexion angles, and smaller peak hip adduction, knee abduction and external rotation angles compared to those who scored a 1. Kinematic differences may not be restricted to the peak joint angle during the OHDS. Therefore, it was additionally hypothesized that groups would express similar differences in joint angles throughout the OHDS.

## Methods

### Study Design

This study utilized a cross-sectional design and participants completed two testing sessions separated by a one-week washout period. During the first session, height and body mass were recorded and participants were asked to perform the OHDS for purposes of dichotomizing participants by FMS OHDS score. During the second session, lower body kinematics of the OHDS were measured. Two sessions were utilized to 1) ensure equal sample size within each group during motion capture analyses 2) provide equivalent exposure and acclimatization to the OHDS because it was a novel task to the sample.

### Participants

An *a-priori* power analysis determined that we needed 39 participants to detect a moderate effect in multivariate analyses ($f = 0.3$, $\beta = 0.2$, $\alpha = 0.05$, number of response variables = 6, expected correlation among measure = 0.5) based on previous studies that compared kinematics between individuals who scored a 1, 2 or 3 on the OHDS of the FMS (Bulgan, 2017; Butler et al., 2010). However, 45 participants (15 per group) were recruited to account for methodological differences and possible subject attrition between sessions. Participants were recreationally active (exercise 30 minutes 3 times per week) and were between the ages of 18 to 30. Participants were excluded if they had any lower extremity injury within the past six months, any history of lower extremity surgery, existing neurological conditions, or prior knowledge of FMS testing and scoring criteria.(Frost et al., 2015) We also excluded those who scored a 0 during their preliminary screening as they may not be able to complete the movement due to pain (Butler et al., 2010). All methods were approved by the university's institutional review board, and participants provided written informed consent prior to participation.

### Procedures

Participants performed the OHDS without warmup in a biomechanics laboratory to ensure that testing in both sessions would occur in a similar environment. They were asked to place a dowel on their head with their elbows flexed at 90º and reach the dowel up overhead. Participants squatted down as low as they could and return to starting position for three repetitions. Two raters who were FMS certified observed and independently scored the OHDS performed by each participant. OHDS was scored per FMS guidelines (Butler et al., 2010; Cook et al., 2014). Participants were provided with a heel lift if a compensation was observed with the feet flat on the ground (i.e. heels were elevated) (Butler et al., 2010; Cook et al., 2014). A third rater who was FMS certified was utilized during sessions if there was not consensus between the two raters, and the majority opinion was ultimately used in analysis. Participants were grouped based on the FMS score that they received, and participants were excluded from the study if they received a score of 0 (Butler et al., 2010). Participants were not told their score and did not receive any feedback on their performance.

Following a one-week washout period, a 9-camera motion capture system (Qualisys, Gothenburg, Sweden) was used to sample lower extremity kinematics during the OHDS at 120 Hz. Participants were instructed to wear spandex shirts and shorts and laboratory standard neutral cushion athletic footwear for motion capture analyses. Standardized footwear was used to control the amount of heel lift that may influence OHDS performance and score. Static calibration markers were positioned bilaterally on the anterior superior iliac spine, greater trochanter, medial and lateral femoral epicondyle, medial and lateral malleoli, calcaneus, and first and fifth metatarsals, and were removed following a standing calibration trial. Clusters of 4 non-collinear rigid markers were placed bilaterally on the thigh, the shank, and foot, and one cluster was placed on the sacrum. Participants performed the OHDS following identical procedures as session 1, and performed three trials of three repetitions each at a self-selected speed.

Data were exported to Visual 3D for model construction (C-Motion Inc., Rockville, MD, USA). Marker trajectories were low-pass filtered using a zero-phase lag fourth-order Butterworth filter at 6 Hz. The hip joint center was estimated as 25% of the distance from the greater trochanter to the contralateral greater trochanter (Bennett et al., 2016). The knee joint and ankle joint centers were estimated as the midpoints between the lateral and medial femoral epicondyles and malleoli, respectively. A modified foot segment was used where the long axis was offset from the heel counter and distal foot markers such that the modified foot segment was parallel to and in line with the floor (Gonzales et al., 2019). Euler/Cardan angles (XYZ rotation sequence) were used to determine relative hip, knee, and ankle angles. Hip motion was defined as movement of the thigh relative to the pelvis, knee joint motion was defined as movement of the shank relative to the femur, and ankle motion was defined as motion of the modified foot relative to shank segment.

The variables of interest included the peak hip flexion angle, peak knee flexion angle, peak knee abduction angle, and peak ankle dorsiflexion angle. Preliminary inspection of the transverse plane knee angle waveform indicated that participants predominately entered knee internal rotation rather than knee external rotation (Figure 1), and thus we evaluated the peak internal knee rotation angle. Similarly, the sample predominately entered hip abduction rather than adduction (Figure 1), and thus we evaluated the peak hip abduction angle. The start and end of each repetition was defined using the vertical velocity of the pelvis segment center of mass (<-1 m/s during descent or <1 m/s during ascent, respectively), and the middle repetition from each trial was used for analysis. Peak values were extracted from each trial and from the limb scored with lower movement quality from day 1 per FMS guidelines, and were averaged for analysis. Kinematic waveforms were time normalized to 101 data points and averaged with 95% confidence intervals for each FMS group.

## Statistical Analyses

Statistical analyses were completed with Statistical Package for the Social Sciences (SPSS Version 24.0; IBM Corporation, New York, USA). Intrasession reliability for all biomechanical variables were calculated during pilot testing (n = 10) using intraclass correlations ($ICC_{3,1}$), and measurement precision was assessed using standard error of the mean. Similarly, we assessed interrater reliability between the two raters of the FMS scores of the OHDS using Cohen's Kappa coefficient.

Data were inspected for univariate normality using the Shapiro-Wilk test, and Box M's test was used to evaluate if the covariance matrices were similar between groups for multivariate analysis. A one-way multivariate analysis of variance (MANOVA) was used to compare kinematic variables between groups ($\alpha = 0.05$). One-way ANOVA and independent samples t-tests were used for post hoc comparisons to identify specific differences in kinematic variables between groups using a Bonferroni adjustment. Time normalized ensemble average waveforms were plotted for each group using MATLAB and regions of the waveforms where 95% confidence intervals did not overlap for 3 consecutive data points were considered statistically different (Goetschius et al., 2018).

## Results

Demographic characteristics by group are summarized in Table 1. Biomechanical outcomes had good to excellent reliability during pilot testing ($ICC_{3,1} > 0.7$, Table 2), and the FMS scores had substantial agreement (Landis and Koch, 1977) between raters (Kappa = 0.62). All data were normally distributed and met the assumptions for MANOVA analyses.

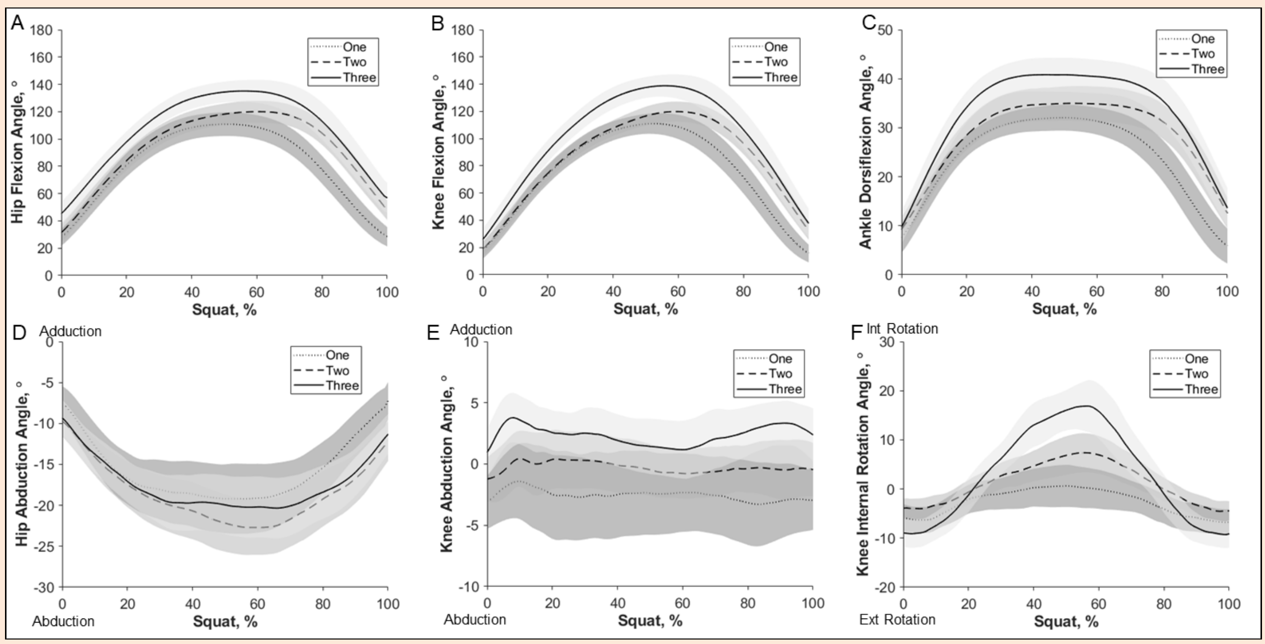


**Figure 1. Time normalized ensemble average waveforms for Hip Flexion Angle (A); Knee Flexion Angle (B); Ankle Dorsiflexion Angle (C); Hip Abduction Angle (D); Knee Abduction Angle (E); Knee Internal Rotation Angle (F).**

**Table 1. Demographic characteristics. Data are means (± standard deviation).**

| | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| **Sex (n)** | 9 female; 6 male | 8 female; 7 male | 9 female; 6 male |
| **Age (years)** | 22.53 (2.13) | 23.13 (1.96) | 22.20 (2.21) |
| **Mass (kg)** | 72.17 (10.90) | 77.91 (13.51) | 73.17 (10.66) |
| **Height (m)** | 1.69 (0.09) | 1.71 (0.06) | 1.68 (0.08) |

**Table 3.** Group means and 95% confidence interval (CI) for biomechanical variables.

| | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| **Peak HFA (°)** | 112.38 (103.73, 121.03) | 120.85 (112.20, 129.5) | 137.32 (128.67, 145.97) *† |
| **Peak HAbA (°)** | -21.02 (-17.28, -24.76) | -23.57 (-19.84, -27.31) | -22.27 (-18.53, -26.01) |
| **Peak KFA (°)** | 114.42 (106.66, 122.18) | 123.14 (115.38, 130.90) | 142.08 (134.32, 149.84) *† |
| **Peak KAbA (°)** | -3.29 (-6.72, 0.12) | -1.25 (-3.02, 0.56) | 0.95 (-1.01, 2.92) |
| **Peak KIRA (°)** | 6.60 (2.86, 10.34) | 9.33 (5.59, 13.07) | 19.26 (15.52, 23.00) *† |
| **Peak DFA (°)** | 33.26 (30.11, 36.40) | 35.96 (32.82, 39.11) | 42.37 (39.22, 45.51) *† |

HFA: Hip Flexion Angle, HAbA: Hip Abduction Angle, KFA: Knee Flexion Angle; KAbA: Knee Abduction Angle, KIRA: Knee Internal Rotation Angle, DFA: Dorsiflexion Angle, * different than group 2, † different than group 1.

**Table 4.** Significant pairwise differences between biomechanical variables.

| | | Mean Difference (CI) | *p* | Eta Squared |
|---|---|---|---|---|
| **Group 3 and Group 1** | **Hip Flexion Angle (°)** | 24.94 (9.82, 40.05) | *0.001 | 0.294 |
| | **Hip Adduction Angle (°)** | 1.65 (-1.66, 4.97) | 0.663 | 0.081 |
| | **Knee Flexion Angle (°)** | 27.66 (14.10, 41.22) | *0.001 | 0.392 |
| | **Knee Abduction Angle (°)** | 3.55 (-0.25, 7.36) | 0.074 | 0.133 |
| | **Knee Internal Rotation Angle (°)** | 12.65 (6.12, 19.19) | *0.001 | 0.318 |
| | **Dorsiflexion Angle (°)** | 9.11 (3.61, 14.60) | *0.001 | 0.300 |
| **Group 3 and Group 2** | **Hip Flexion Angle (°)** | 16.47 (1.35, 31.58) | *0.029 | 0.294 |
| | **Hip Adduction Angle (°)** | 0.85 (-2.45, 4.17) | 0.999 | 0.081 |
| | **Knee Flexion Angle (°)** | 18.94 (5.38, 32.50) | *0.004 | 0.392 |
| | **Knee Abduction Angle (°)** | 0.44 (-3.36, 4.24) | 0.985 | 0.133 |
| | **Knee Internal Rotation Angle (°)** | 9.93 (3.39, 16.46) | *0.001 | 0.318 |
| | **Dorsiflexion Angle (°)** | 6.40 (0.90, 11.90) | *0.018 | 0.295 |

* significant difference after Bonferroni adjustment

**Table 2.** Reliability analyses from pilot testing (n = 10).

| Kinematic Variable | ICC (Model 3,1) | SEM |
|---|---|---|
| **Peak HFA (°)** | 0.994 | 0.71 |
| **Peak HAbA (°)** | 0.971 | 1.29 |
| **Peak KFA (°)** | 0.987 | 1.73 |
| **Peak KAbA (°)** | 0.866 | 2.61 |
| **Peak KIRA (°)** | 0.737 | 4.76 |
| **Peak DFA (°)** | 0.805 | 3.21 |

There was a significant effect of FMS score on OHDS biomechanics ($F_{2, 42}$ = 3.48; p = 0.001, eta squared = 0.401). Participants who scored a 3 had a greater peak hip flexion angle, knee flexion angle, knee internal rotation angle, and dorsiflexion angle compared to those who scored a 2 and a 1 (Table 3, Table 4). No differences were found between any of the groups in the peak hip abduction angle, and peak knee abduction angle. Moreover, no differences were identified in any peak biomechanical outcome between those who scored a 2 and 1 (Table 3).

Evaluation of the time normalized ensemble average waveforms of the OHDS indicated that there were differences throughout the OHDS that were not restricted to the peak values (Figure 1). Participants who scored a 3 had a larger hip flexion angle compared with those who scored a 2 from 31-51% of the squat, and a larger hip flexion angle compared with those who scored a 1 throughout the entire squat. Individuals who scored a 2 had a larger hip flexion angle compared with those who scored a 1 from 72-100% of the squat.

Participants who scored a 3 had a larger knee flexion angle compared with those who scored a 2 from 15-63% of the squat, and a larger knee flexion angle compared with those who scored a 1 from 17-100% of the squat. Participants who scored a 2 had a larger knee flexion angle compared with those who scored a 1 from 73-100% of the squat.

Participants who scored a 3 had greater dorsiflexion compared with those who scored a 1 from 16-98% of the squat. Participants who scored a 2 had greater dorsiflexion compared with those who scored a 1 from 83-97% of the squat.

Participants who scored a 3 had a larger knee internal rotation angle compared with those who scored a 2 from 38-55% of the squat, and a larger knee internal rotation angle compared with those who scored a 1 from 29-72%. Those who scored a 2 also had a larger knee internal rotation angle compared with those who scored a 1 from 31-83% of the squat. No differences were observed between the groups throughout the squat in the hip abduction or knee abduction angle.

## Discussion

The main findings of this study were that those who scored a 3 had a larger peak hip flexion angle, knee flexion angle, knee internal rotation angle and dorsiflexion angle compared to those who scored a 2 or a 1. However, no differences were found in peak hip flexion angle, knee flexion angle, knee internal rotation angle and dorsiflexion angle between those who scored a 1 and those who scored a 2. We also observed differences between groups in the hip flexion angle, knee flexion angle, knee internal rotation angle and dorsiflexion angle at various portions of the OHDS when inspecting the ensemble average waveforms.

Our findings only partially supported our hypotheses as we did not observe differences between those who scored a 1 or 2 in peak hip flexion, knee flexion, or ankle dorsiflexion. Peak hip flexion, knee flexion, and dorsiflexion angles are during the OHDS are representative of squat depth (Bulgan, 2017; Butler et al., 2010; Jenkins et al., 2017). However, squat depth is determined in the FMS using the position of the femur relative to the ground (Myer et al., 2014). The FMS scoring criteria for a 3 on the OHDS states that an individual must maintain an upright torso, femur below parallel with the ground, and knees aligned over the feet (Cook et al., 2014). A score of 2 has identical criteria as a 3 but a single exception that the heels are elevated (Cook et al., 2014). An elevated heel may reposition the foot, shank, and thigh segments and likely contribute to the differences found in knee and hip flexion and ankle dorsiflexion between those who scored a 3 and 2. Conversely, a score of 1 is differentiated from a 2 via multiple factors, such as the femur being above the horizontal or the knees not being aligned over the feet. Individuals who score a 1 may not possess both of these characteristics, which may have contributed to the lack of difference in hip and knee flexion, and ankle dorsiflexion between those who scored a 2 and those who scored a 1.

A decrease in sagittal plane hip range of motion (<120º) or dorsiflexion can be a contributing factor in OHDS performance based on FMS score indicating limitations in movement (Butler et al., 2010; Cook et al., 2014; Jenkins et al., 2017), and a lack of hip flexion or dorsiflexion may place additional strain on the knee. Previous studies have found a difference in hip flexion and knee flexion between those who scored a 3 or 2 compared to those who scored a 1, but no difference between those who scored a 3 and a 2 (Bulgan, 2017; Butler et al., 2010). Similarly, we found that the FMS scoring system may not be able to distinguish between 3 levels of movement dysfunction. Furthermore, the OHDS may be limited to assess movement quality compared to other squat variations. For instance, individuals may display adequate depth when unaccompanied by an overhead component or by squatting with a wider stance (McMillian et al., 2016).

Our findings indicate that the FMS score of the OHDS primarily identifies differences in squat depth. However, clinicians should further evaluate individuals with limited squat depth since the source of restriction is unclear from the score. For instance, restricted ankle dorsiflexion may relate to capsular tightness, soft tissue restrictions of the foot and posterior lower leg musculature (Myer et al., 2014). Furthermore, restricted ankle movement may limit sagittal plane tibial motion, and concurrently contribute to compensatory motions such as increased foot pronation, talar eversion, and tibial internal rotation (Mauntel et al., 2015). Secondly, the magnitude of hip flexion may be influenced by the anatomical structure of the femoroacetabular joint, soft tissue restriction, or hip extensor weakness (Cheatham et al., 2018; Myer et al., 2014). If an individual lacks depth with hip flexion, it may be due to the individual possessing a deep femoroacetabular joint (Myer et al., 2014), whereas a shallow femoroacetabular joint would allow for more depth with hip flexion. This may indicate that anatomical structure may influence movement patterns regardless of neuromuscular impairment, which has implications for appropriate intervention selection. Finally, we note that there may be kinematic differences in trunk and shoulder motion that may also influence squat depth that were not assessed. For example, additional thoracic extension and shoulder flexion may aid in altering the total body center of mass position, and thus contribute to additional squat depth.

Contrary to our hypotheses, there were no differences in peak values for frontal plane hip and knee motion, which could indicate that the FMS scoring criteria for the OHDS lack a consistent criterion to assess frontal plane knee and hip kinematics. Moreover, visualization of the frontal plane hip angle waveform suggested that the sample, on average, entered a knee varus position rather than valgus position regardless of FMS score. Previous studies evaluating the FMS did not measure the frontal plane hip or knee angle during the OHDS (Bulgan, 2017; Butler et al., 2010). However, the FMS scoring criteria does state that knees should be aligned over the feet in the frontal plane (i.e. "knees track inside of feet").(Butler et al., 2010; Cook et al., 2014) Additionally, greater frontal plane hip motion is associated with aberrant movement patterns during other tasks (e.g. landing) (Donohue et al., 2015; Hewett et al., 2005; Padua et al., 2009).

The OHDS of the FMS was examined because it contributes the largest proportion of variance to total composite score relative to the other FMS tasks (Kraus et al., 2015). However, hip adduction and knee abduction may be more commonly observed during unilateral movements such as cutting maneuvers, a lateral step down, a step up, or a single-leg squat (Earl et al., 2007; Jones et al., 2014; Paz et al., 2016), or high velocity bilateral movement such as a drop-vertical jump (Hewett et al., 2005). Similarly, increases in hip adduction and knee abduction may be more identifiable during a drop landing compared to an OHDS due to greater movement velocity and high impact forces (Hewett et al., 2005; Padua et al., 2009), Therefore, multiple tests are necessary to assess frontal and transverse plane hip and knee motion rather than relying on the OHDS during the FMS, and future studies are needed to determine if FMS scores are associated with movement patterns during other tasks (e.g. drop landing, cutting etc.).

We found that those who scored a 3 had a larger peak knee internal rotation angle and larger knee internal rotation angle throughout the OHDS compared to those who scored a 2 and those who scored a 1. Though knee external rotation is observed with dynamic valgus,(Ishida et al., 2012) we observed that our sample, on average, entered a knee internal rotation position during the squat. The higher knee internal rotation angle values in participants who scored a 3 compared to a 2 or 1 are likely attributed to greater knee flexion. Knee internal rotation is necessary to unlock the knee and allow for more depth during a squat, and greater knee flexion is associated with greater knee internal rotation (Ishida et al., 2012; Zarins et al., 1983). Due to the arthrokinematics and alignment of the tibiofemoral joint, the tibia will internally rotate relative to the femoral condyles (Zarins et al., 1983). At 90º of knee flexion, individuals possess approximately 25º of passive knee internal rotation (Zarins et al., 1983), and the knee will begin to internally rotate at 30º of knee flexion (Ishida et al., 2012). Therefore, clinicians should consider the magnitude of knee flexion when interpreting if greater peak knee internal rotation is a potentially hazardous movement on an individual basis. For instance, greater knee internal rotation observed in the presence of lower knee flexion may place additional stress on internal knee structures. Excessive knee internal rotation is considered a hazardous biomechanical movement that may contribute to injury (Earl et al., 2007;

Padua et al., 2009; Rabin et al., 2016). For example, excess knee internal rotation during unilateral movements may contribute to ACL injury risk (Ishida et al., 2012; Padua et al., 2009), and unilateral tasks may be better suited to assess transverse plane knee motions.

Study strengths included an exclusion criterion that excluded those with past knowledge of the FMS to ensure consistent exposure to the OHDS assessment between all participants. Previous research indicates that prior knowledge of the FMS and its scoring criteria influence participants' performance (Frost et al., 2015). Secondly, we used multiple raters who were FMS-certified to evaluate all movements, which likely improved the scoring validity. We note that the agreement between raters was moderate to substantial (Landis and Koch, 1977), and this was consistent with past literature evaluating the OHDS (Garrison et al., 2015; Minick et al., 2010; Shultz et al., 2013).

There are limitations to consider when interpreting the results of this study. Firstly, we only assessed lower extremity kinematics. Trunk kinematics, such as forward trunk lean may contribute to an increase in the relative hip flexion angle and a decrease in knee flexion, and also influence the moment arm at the hip and knee via the vector of the ground reaction force. Therefore, it is important to consider trunk mechanics in future studies to differentiate between FMS scoring categories. Thirdly, we utilized two sessions where participants were first screened and dichotomized to scoring groups, and then assessed 3-dimensional OHDS biomechanics during a second session following a 1-week washout period. While we cannot rule out a learning effect of the OHDS, we note that the washout between sessions was standardized between participants and no feedback on score or performance was provided between sessions. This method standardized the amount of exposure, while simultaneously provided acclimatization to a novel task. Previous research also indicates good test-retest reliability of FMS scores when using a 1-week washout (Shultz et al., 2013). Finally, we did not consider anthropometric contributors to OHDS score, which may also influence joint and segment kinematics and should be considered in future studies.

## Conclusion

Those who scored a 3 in the OHDS had greater peak hip flexion, knee flexion, knee internal rotation, and dorsiflexion angles compared to those who scored a 2 or a 1, but no differences were found in peak values between those who scored a 1 and 2. Conversely, only subtle differences were found between those scored a 1 and 2 at later time points throughout the OHDS in the hip flexion, knee flexion, and dorsiflexion angles. As such, clinicians should interpret scores of 1 and 2 with caution because these individuals may be more difficult to visually distinguish. Additionally, these findings may indicate that the FMS scores of the OHDS primarily reflect squat depth, and the FMS could be useful where 3-dimensional biomechanical analyses are unavailable. Clinicians may not be able to assess excessive frontal or transverse plane hip and knee movement using an OHDS. Clinicians should consider incorporating other movements in a battery of testing, such as a drop landing or lateral step down, to assess for frontal and transverse plane mechanics.

### Acknowledgements
The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author who was an organizer of the study.

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## Key points

- The FMS scoring criteria of the OHDS largely identified differences in squat depth
- Other tasks are needed to evaluate frontal and transverse plane movement patterns.
- The FMS scoring criteria of the OHDS may be unable to categorize individuals across 3 levels, and caution is needed when comparing scores of 2 and 1. Kinematic evaluations should not be limited to the peak value, as kinematic differences between scoring FMS categories is evident throughout the OHDS.


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