

Biomechanical Comparison of Single- and Double-Leg Jump Landings in the Sagittal and Frontal Plane

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Background: Double-leg forward or drop-jump landing activities are typically used to screen for high-risk movement strategies and to determine the success of neuromuscular injury prevention programs. However, research suggests that these tasks that occur primarily in the sagittal plane may not adequately represent the lower extremity biomechanics that occur during unilateral foot contact or non-sagittal plane movements that are characteristic of many multidirectional sports.

Purpose: To examine the extent to which lower extremity biomechanics measured during a jump landing on a double leg (DL) after a sagittal plane (SAG) movement is representative of biomechanics measured during single-leg (SL) or frontal plane (FRONT) jump landing tasks.

Study Design: Controlled laboratory study.

Methods: Lower extremity biomechanics were measured in 15 recreationally active females (mean age [\pm SD], 19.4 ± 2.1 years; mean height, 163.3 ± 5.9 cm; mean weight, 61.1 ± 7.1 kg) while performing SAG_{DL}, SAG_{SL}, FRONT_{DL}, and FRONT_{SL} jump landing tasks. Repeated-measures analyses of variance examined differences in lower extremity biomechanics between the 4 tasks, and linear regressions examined the extent to which an individual's biomechanics during SAG_{DL} were representative of their biomechanics during SAG_{SL}, FRONT_{DL}, and FRONT_{SL}.

Results: Lower extremity kinematics and kinetics differed by condition, with the SAG_{DL} task generally eliciting greater hip and knee flexion angles and lower hip and knee forces than the other tasks ($P < .05$). Although biomechanics during the SAG_{DL} task were strongly associated with those during the FRONT_{DL} task (R^2 , 0.41-0.82), weaker associations were observed between SAG_{DL} and single-leg tasks for hip kinematics (R^2 , 0.03-0.25) and kinetics (R^2 , 0.05-0.20) and knee abduction moments (R^2 , 0.06-0.18) ($P < .05$).

Conclusion: Standard double-leg sagittal plane jump landing tasks used to screen for ACL injury risk and the effectiveness of ACL injury prevention programs may not adequately represent the lower extremity biomechanics that occur during single-leg activities.

Clinical Relevance: These results support further investigation of single-leg multidirectional landings to identify high-risk movement strategies in female athletes playing multidirectional sports.

Keywords: anterior cruciate ligament; screening; injury prevention; multidirectional movement

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In multidirectional women's sports, up to 70% of all anterior cruciate ligament (ACL) injuries occur via a noncontact mechanism.¹ Typically, these injuries occur during single-leg, decelerating change-of-direction activities, such as jump landing, cutting, and pivoting.⁴⁰ Specific lower extremity movement patterns, including higher levels of knee abduction and internal rotation and low levels of hip and knee flexion, have been observed at the time of ACL injury.^{4,18,22,24} These motions are consistent with cadaveric studies of ACL loading patterns that report the highest levels of ACL loading with combinations of joint compression, anterior tibial translation, knee abduction, and knee

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internal rotation at shallow knee flexion angles.^{9,27,29} As such, lower extremity biomechanics, including shallow hip and knee flexion, and components of dynamic valgus collapse (hip adduction/internal rotation, knee abduction/internal rotation/external rotation) have been studied prospectively to identify specific movement patterns that may place an athlete at risk of future ACL injury or to ascertain the effectiveness of ACL injury prevention programs.^{13,16,34}

Current biomechanical tests used to screen for high-risk movement patterns emphasize double-leg sagittal plane landings, such as the drop vertical jump, tuck jump, and broad jump.^{8,31,33} Hewett et al¹⁶ reported that greater levels of knee abduction peak angles and forces elicited during a drop vertical jump were predictive of subsequent ACL injury in a cohort of healthy high school female athletes. Using modifications of double-leg sagittal plane tasks, other prospective studies have reported mixed results regarding the extent to which lower extremity biomechanics are predictive of future injury risk.^{13,34,43} Double-leg sagittal plane landings are also conventionally used as the primary method to measure the biomechanical adaptations that result after injury prevention programs. Although evidence indicates that ACL injury prevention programs effectively modify lower extremity biomechanics^{7,17,25} and reduce the risk of injury,⁴⁴ non-contact ACL injuries continue to occur at a relatively high rate, and these programs are not effective in all populations.^{30,37} These findings suggest that although current screening batteries provide valuable information, they may not represent a comprehensive view of an athlete's high-risk biomechanics.

Over 70% of ACL injuries occur during unilateral foot contact, requiring the athlete to bear all bodyweight through a single limb.^{4,10,14,32,35} Additionally, ACL injury incidence rates are reported to be highest in multidirectional sports that are characterized by repetitive movements outside of the sagittal plane.^{4,19} Women's basketball, in particular, requires high levels of single-leg activities (eg, jump landings, cutting, pivoting) and more frequent purposeful movements in the frontal plane (eg, lateral shuffling and cutting) than in the sagittal plane (eg, sprinting) during live game action.²⁸ Given these sport demands, double-leg sagittal plane movements, although providing meaningful data, may not fully represent the neuromuscular strategies that female athletes utilize during high-risk activities. This is supported by findings from previous research that the biomechanics employed during double-leg drop vertical jumps are not predictive of movement strategies during single-leg cutting tasks.^{21,23} In addition to differences between jumping and cutting, evidence suggests that significantly more strenuous biomechanical demands occur when landing on a single leg compared with a double leg^{10,14,32,35} or landing after movement in the frontal plane compared with the sagittal plane.^{12,41,42} Whether the variations of these tasks elicit biomechanics that are a function of a standard double-leg jump landing task or are independent of these measures is crucially important to optimize ACL injury screening procedures. Understanding the extent to which biomechanics during a double-leg sagittal plane landing are predictive of single- and double-leg

actions in other planes of motion may identify additional biomechanical tasks to complement current assessment methods for examining ACL injury risk potential and the effectiveness of ACL injury prevention programs.

Thus, the purposes of this study were to examine (1) the performance consistency of various potential jump landing screening tasks and (2) the extent to which lower extremity biomechanics measured during a double-leg sagittal plane jump landing predict the biomechanics measured during single-leg sagittal plane, double-leg frontal plane, or single-leg frontal plane jump landing tasks. We hypothesized that based on the demands of the different tasks, there would be significant differences in lower extremity biomechanics between planes of movement (sagittal, frontal) and landing base of support (double and single leg) such that high-risk biomechanics, especially higher levels of dynamic lower extremity valgus (eg, hip adduction, hip internal rotation, knee abduction) and shallower hip and knee flexion angles would be more predominant during the single-leg sagittal and frontal plane tasks than the standard double-leg sagittal plane task. We further expected that the biomechanical pattern exhibited during double-leg sagittal plane landing would not predict the biomechanical pattern elicited during the other landings tested (ie, lower extremity biomechanics observed during the double-leg sagittal plane jump landing task would not be predictive of those during single-leg and non-sagittal plane tasks).

METHODS

Participants

Fifteen recreationally active, collegiate-aged females (mean age \pm SD), 19.4 ± 2.1 years; mean height, 163.3 ± 5.9 cm; mean weight, 61.1 ± 7.1 kg) were recruited for inclusion in this study. Subjects were included if they had previously participated in at least 1 competitive multidirectional or jumping sport at a high school competitive level or above (basketball, $n = 2$; field hockey, $n = 3$; lacrosse, $n = 4$; soccer, $n = 5$; softball, $n = 2$; volleyball, $n = 2$) and were medically cleared to participate in running, jumping, and cutting tasks. Potential subjects were excluded if they had suffered a lower extremity injury in the previous 6 months or had a history of vestibular or connective tissue disorder. Participants were screened for eligibility and provided informed written consent approved by the High Point University Institutional Review Board. Each participant reported to the research laboratory on 2 separate occasions (2-5 days apart). Biomechanical data from both testing sessions were used to analyze the performance consistency of each task, and data from the second session were used to analyze and compare the biomechanical demands of each jump landing task.

Instrumentation

Each subject was instrumented for 3-dimensional biomechanical analysis with 43 reflective markers placed on the sternum, sacrum, left posterior superior iliac spine, C7, 3

points on the upper back (via a thin backpack), and bilaterally on the shoulder, upper arm, elbow, wrist, anterior superior iliac spine, greater trochanter, mid thigh, medial and lateral knee joint line, tibial tubercle, midshank, distal shank, medial and lateral malleolus, and to the foot at the heel, dorsal surface of the lateral midfoot, lateral rear foot, and toe via adhesive tape to laboratory provided footwear (Adidas Adipure 360.2; Adidas).² A static trial was collected to determine each subject's neutral alignment and anatomically define each body segment, by which subsequent biomechanical measures were referenced. Three-dimensional motion data were collected with Cortex software (version 5; Motion Analysis Corp) using a 14-camera system (Eagle cameras; Motion Analysis Corp) that sampled at 200 Hz. Kinetic data were sampled at 1200 Hz and collected by dual, in-ground, multi-axis force plates (90 × 60 cm) (AMTI) such that each force plate collected data from a single leg.

Procedures

Prior to performing jump landing tasks, multiple repetitions (3-5) of a countermovement jump were performed to establish each subject's maximal vertical jump reach with arms over their head. An overhead target has been reported to promote higher intensities when performing a maximal vertical jump¹¹; therefore, a target was set at each subject's maximal countermovement vertical jump reach for use during all subsequent jump landing tasks. Four jump landing tasks were used in this study and were selected because of their similar demands (horizontal translation to vertical translation) and abilities to tease out differences in movement plane and double- versus single-leg landings. The order of the jump landing tasks was randomized for each participant prior to the start of the study, and subjects performed tasks in the same order at both testing sessions. Each subject performed 1 to 3 practice trials of each exercise until the subject felt comfortable with the task and the investigator deemed the performance adequate. After practice, each task was performed 3 times while lower extremity biomechanics were recorded.

Sagittal Plane Tasks

The double-leg sagittal plane task (SAG_{DL}) was a standard broad jump with subsequent maximal vertical jump. Participants were positioned a distance equal to their leg length (greater trochanter to lateral malleolus) from the edge of the force plates. Participants were instructed to jump forward, aiming for the center of the force plates, land with both feet at the same time, and immediately perform a maximal vertical jump, reaching up for the target with both hands (Figure 1A). Although the drop vertical jump is the most common ACL injury screening test, we chose to use a double-leg broad jump as the standard double-leg sagittal plane task because it required the most comparable biomechanical demands to the other tasks used in this study. We hypothesized that if differences were identified between comparable tasks, more robust differences would be seen between the drop vertical jump and other multidirectional tasks. Furthermore, it has been reported that a double-leg

broad jump promotes lower extremity biomechanics that may place an athlete at greater risk than during a drop vertical jump, including greater anterior tibial shear forces and lower extremity energy absorption requirements,⁸ thereby suggesting that a broad jump may be more specific to the sport tasks that are associated with ACL injury.

Similar methods were used for the single-leg broad jump (SAG_{SL}), though the subject was positioned a distance equal to one-half of their leg length away from the force plates and were asked to jump off 1 leg, land on the same leg, and immediately perform a maximal vertical jump, attempting to reach the target with the contralateral hand (Figure 1B). The contralateral upper extremity was used as the reaching arm during all single-leg landings because it was deemed to most resemble athletic movements of multidirectional jumping sports. The SAG_{SL} task was performed 3 times on each leg.

Frontal Plane Tasks

For the double-leg frontal plane task (FRONT_{DL}), participants were instructed to perform a lateral jump with double-leg landing followed immediately by a maximal vertical jump. Participants stood straddling a line placed a distance equal to one-half of their leg length away from the edge of the nearest force plate. Participants were instructed to keep their trunk facing forward while performing a lateral jump such that each foot landed on a separate force plate at the same time and immediately perform a maximal vertical jump, reaching for the target with both hands (Figure 1C). Similar techniques were used for the single-leg lateral jump hop (FRONT_{SL}). Participants were again placed at a distance equal to one-half of their leg length away from the closest force plate, standing on their outside leg. They were instructed to jump to the middle of the second force plate (located 36 cm plus one-half of leg length away), land on the opposite limb, and immediately perform a maximal vertical jump, reaching toward the target with the hand contralateral to the landing limb (Figure 1D). Participants performed the FRONT_{DL} and FRONT_{SL} tasks in both directions.

Data Analysis and Reduction

Landing phase data of the initial rebound movement (transition from horizontal to vertical translation), from initial contact (vertical ground reaction force >10 N) to maximal descent (center of gravity at lowest point) of the first jump landing (prior to maximal vertical jump) were imported into Visual3D (version 5; C-Motion Inc). Hip joint centers were calculated using the Bell method,³ and the knee and ankle joint centers were calculated as the centroid position of the medial and lateral femoral epicondyles and malleoli, respectively. Joint moments, calculated using inverse dynamics, and kinematic data were filtered through a fourth-order, low-pass digital filter with a cutoff frequency of 12 Hz. Biomechanical data from the left lower extremity were then processed using MATLAB software (version 8.0; The Mathworks). The left limb was selected because it was uniformly identified by the entire sample as the preferred stance limb when kicking a ball

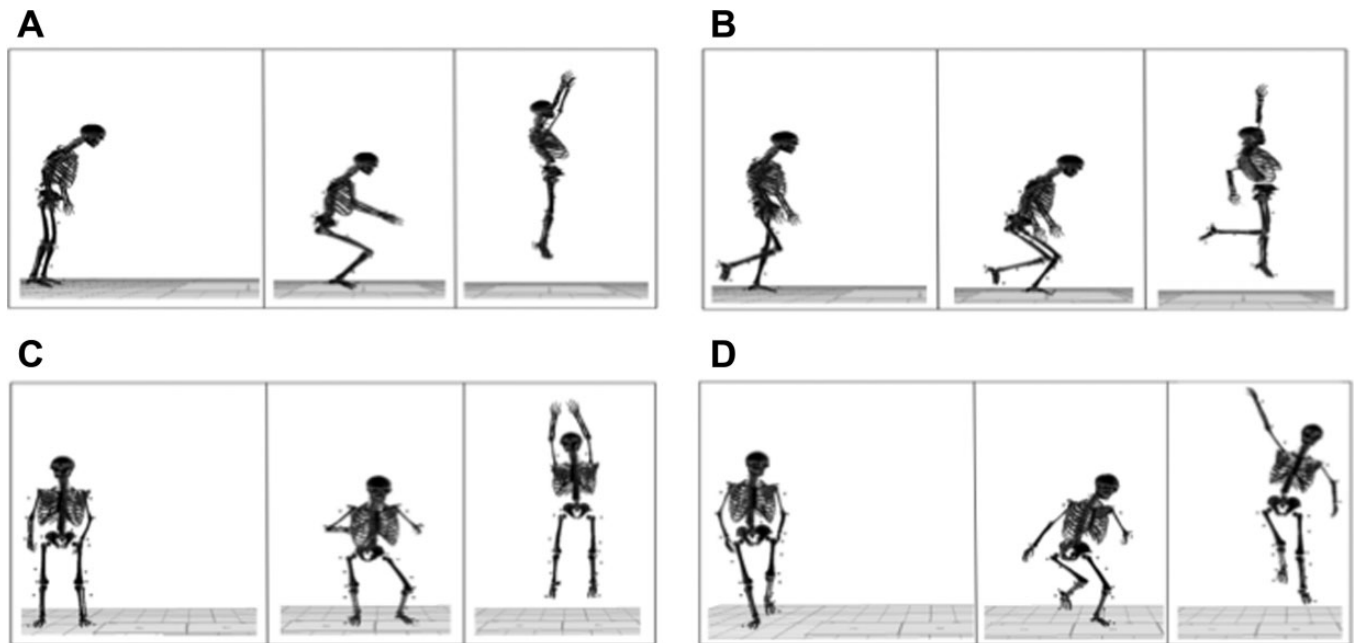


Figure 1. Representations of each task: (A) SAG_{DL}, (B) SAG_{SL}, (C) FRONT_{DL}, and (D) FRONT_{SL}. DL, double leg; FRONT, frontal plane; SAG, sagittal plane; SL, single leg.

and therefore may suffer the majority of ACL injuries in female athletes.⁵ Biomechanical variables of interest included peak hip flexion, adduction, and internal rotation and knee flexion, abduction, internal and external rotation angles, and external moments. Hip flexion, adduction, and internal rotation and knee extension, adduction, and internal rotation were reduced as positive motions. Moments were normalized to mass (kg) and height (m) for more accurate between-subject comparisons. These variables were selected based on the collective thought that they may either influence dynamic valgus collapse or promote stiff-legged landings, theorized as the predominant mechanisms of ACL injury in female athletes.^{15,38,39} Means of all 3 trials for each task were calculated and used in statistical analyses.

Statistical Analysis

All statistical analyses were performed using SPSS version 22 (IBM Corp).

Performance Consistency/Reliability. Peak sagittal, frontal, and transverse plane kinematic and kinetic variables from the hip and knee were analyzed for performance consistency and precision of measurement. The mean of 3 trials from the left lower limb was used for analysis. Intra-class correlation coefficients and standard error of measurements (ICC_{2,k} [SEM]) were calculated to examine between-session reliability and the precision of measurement, respectively. Standard ICC classifications were used such that ICC values greater than 0.75 were considered excellent, 0.60 to 0.75 were considered good, 0.40 to 0.60 were considered fair, and less than 0.40 were considered poor.³⁶

Biomechanical Comparison of Tasks. To examine the effects of movement plane and landing base of support on hip and knee biomechanics, 2 (sagittal vs frontal plane) × 2 (double-leg vs single-leg landing base of support) repeated-measures analyses of variance (ANOVAs) were performed. Post hoc planned pairwise comparisons of significant main effects and plane × base of support interactions were performed with paired-sample *t* tests to identify whether the SAG_{SL}, FRONT_{DL}, or FRONT_{SL} tasks elicited different hip and knee biomechanics than the standard SAG_{DL} task. Significance was set a priori for all analyses at $\alpha = 0.05$, and Cohen *d* effect sizes were calculated for all statistically significant interactions.

Relationship of Movement Strategies Between Tasks. Univariate linear regression analyses examined the extent to which movement strategies employed during the standard SAG_{DL} task predicted movement strategies during the other frontal and single-leg landing tasks ($\alpha = 0.05$). Secondary regression analyses examined biomechanical relationships between the 2 single-leg landing tasks.

RESULTS

Performance Consistency

Between-session ICC and SEM values for all biomechanical variables are reported in Table 1. All tasks showed comparable performance consistency between sessions, with ICC values ranging from good to excellent (>0.60). Precision of peak kinematic measurements were acceptable and consistent between tasks, with SEMs ranging from 1.4° to 4.1°.

TABLE 1
Between-Session Reliability for Peak Kinematic
and Kinetic Variables of All Tasks^a

	SAG _{DL}	SAG _{SL}	FRONT _{DL}	FRONT _{SL}
Kinematics: peak angle during landing phase, deg				
Hip flexion	0.86 (3.1)	0.86 (3.4)	0.71 (4.1)	0.84 (3.2)
Hip adduction	0.87 (1.8)	0.87 (2.0)	0.89 (2.5)	0.79 (3.5)
Hip internal rotation	0.86 (2.9)	0.63 (3.5)	0.94 (1.9)	0.84 (3.2)
Knee flexion	0.87 (2.1)	0.95 (1.4)	0.94 (1.6)	0.90 (2.0)
Knee abduction	0.87 (1.8)	0.90 (1.7)	0.81 (3.0)	0.84 (2.0)
Knee internal rotation	0.95 (1.7)	0.90 (2.0)	0.80 (2.2)	0.89 (1.6)
Knee external rotation	0.85 (1.9)	0.85 (1.9)	0.89 (2.0)	0.84 (2.3)
Kinetics: peak moments during landing phase, N-m				
Hip flexion	0.74 (10.5)	0.82 (29.8)	0.88 (9.6)	0.84 (13.3)
Hip adduction	0.80 (3.9)	0.94 (7.7)	0.92 (4.6)	0.88 (8.8)
Hip internal rotation	0.80 (5.3)	0.82 (7.1)	0.80 (6.3)	0.70 (9.2)
Knee flexion	0.91 (5.9)	0.91 (7.5)	0.91 (7.3)	0.90 (8.5)
Knee abduction	0.88 (3.4)	0.85 (4.3)	0.78 (5.0)	0.93 (5.1)
Knee internal rotation	0.90 (2.0)	0.63 (2.7)	0.87 (2.0)	0.97 (2.0)
Knee external rotation	0.93 (1.4)	0.97 (1.7)	0.92 (2.8)	0.87 (3.7)

^aData are presented as intraclass correlation coefficient_{2,3} (standard error of the mean). DL, double leg; FRONT, frontal plane; SAG, sagittal plane; SL, single leg.

Biomechanical Comparison of Tasks (ANOVA Results)

Differences in kinematic and kinetic measures between tasks are graphically represented in Figure 2. Significant differences were observed between sagittal and frontal plane movements, between double- and single-leg landings, and between double- and single-leg landings by movement plane ($P < .05$).

Compared with frontal plane landings, sagittal plane landings elicited larger peak hip adduction ($P < .001$) and knee internal rotation ($P = .01$) angles and lower peak hip internal rotation ($P = .01$) and knee external rotation angles ($P < .001$). This was accompanied by greater peak hip flexion ($P < .001$), hip adduction ($P < .001$), knee flexion ($P < .001$), and knee external rotation moments ($P = .02$) and lower peak knee abduction ($P = .007$) and internal rotation moments ($P = .003$) in sagittal plane landings.

Compared with single-leg landings, double-leg landings promoted softer landings with deeper peak hip ($P < .001$) and knee ($P < .001$) flexion angles and elicited lower peak hip adduction angles ($P < .001$) and lower peak hip flexion ($P < .001$), hip adduction ($P < .001$), hip internal rotation ($P < .001$), knee flexion ($P < .001$), knee abduction ($P = .02$), and knee external rotation moments ($P < .001$).

Significant interactions were observed between plane of movement and double- versus single-leg landing support for the majority of kinematic (hip flexion, hip adduction,

and knee flexion) and kinetic (hip flexion, hip adduction, hip internal rotation, knee flexion, knee abduction, and knee external rotation) variables (Figure 2). Compared with SAG_{DL}, SAG_{SL} elicited greater peak hip adduction angles ($P < .001$, $d = 2.26$) and shallower peak hip ($P < .001$, $d = 2.52$) and knee ($P < .001$, $d = 4.49$) flexion angles. Additionally, SAG_{SL} elicited greater peak hip flexion ($P < .001$, $d = 3.84$), hip adduction ($P < .001$, $d = 6.10$), hip internal rotation ($P < .001$, $d = 2.25$), knee flexion ($P < .001$, $d = 2.51$), knee internal rotation ($P = .02$, $d = 1.06$), and knee external rotation ($P < .001$, $d = 5.87$) moments.

Compared with the SAG_{DL}, FRONT_{DL} elicited lower peak hip flexion ($P < .001$, $d = 0.94$), hip adduction ($P < .001$, $d = 1.74$), and knee flexion ($P < .001$, $d = 1.24$) angles and higher hip internal rotation ($P = .002$, $d = 0.92$) and knee internal rotation ($P = .01$, $d = 0.52$) moments than the SAG_{DL}.

Compared with the SAG_{DL} task, FRONT_{SL} was characterized by higher peak hip adduction ($P = .002$, $d = 1.17$), lower peak hip ($P < .001$, $d = 2.24$) and knee flexion ($P < .001$, $d = 3.79$) angles, and higher hip flexion ($P = .01$, $d = 1.05$), hip adduction ($P < .001$, $d = 4.77$), hip internal rotation ($P < .001$, $d = 1.48$), knee abduction ($P = .004$, $d = 1.19$), and knee external rotation moments ($P < .001$, $d = 4.33$).

Relationship of Movement Strategies Between Tasks (Regression Results)

Results of the linear regression analyses examining the associations in lower extremity biomechanics between tasks are reported in Table 2.

In all cases, kinematic (R^2 , 0.42-0.83; $P < .05$) and kinetic (R^2 , 0.42-0.67; $P < .05$) variables elicited during the SAG_{DL} task were largely representative of the corresponding biomechanics elicited during FRONT_{DL} tasks; however, relationships were appreciably weaker when examining associations between SAG_{DL} and the 2 single-leg tasks. When comparing SAG_{DL} and SAG_{SL}, moderate to strong relationships were observed between knee kinematic variables (R^2 , 0.42-0.75; $P < .05$) and knee flexion moments (R^2 , 0.42; $P = .01$). However, peak angles for hip flexion (R^2 , 0.07), adduction (R^2 , 0.04), and internal rotation (R^2 , 0.26) and peak external moments for hip flexion (R^2 , 0.07), adduction (R^2 , 0.08), internal rotation (R^2 , 0.002) and knee abduction (R^2 , 0.23), external rotation (R^2 , 0.11) and internal rotation (R^2 , 0.02) during SAG_{DL} were not representative of those during SAG_{SL} ($P > .05$).

Similarly, strong predictive relationships were identified for the SAG_{DL} and FRONT_{SL} task in all knee kinematic variables (R^2 , 0.40-0.64; $P < .05$) and hip internal rotation (R^2 , 0.27; $P = .05$), knee flexion (R^2 , 0.40; $P = .01$), and internal rotation (R^2 , 0.26; $P = .05$) moments. However, SAG_{DL} was not predictive of FRONT_{SL} for hip flexion (R^2 , 0.08), adduction (R^2 , 0.13), and internal rotation (R^2 , 0.21) peak angles and kinetic strategies for hip flexion ($R^2 < 0.001$), adduction (R^2 , 0.03), and knee abduction (R^2 , 0.05) and external rotation (R^2 , 0.001) moments ($P > .05$). Lower extremity hip and knee kinematics during SAG_{SL} were largely representative of those during FRONT_{SL} tasks ($P < 0.05$), yet hip

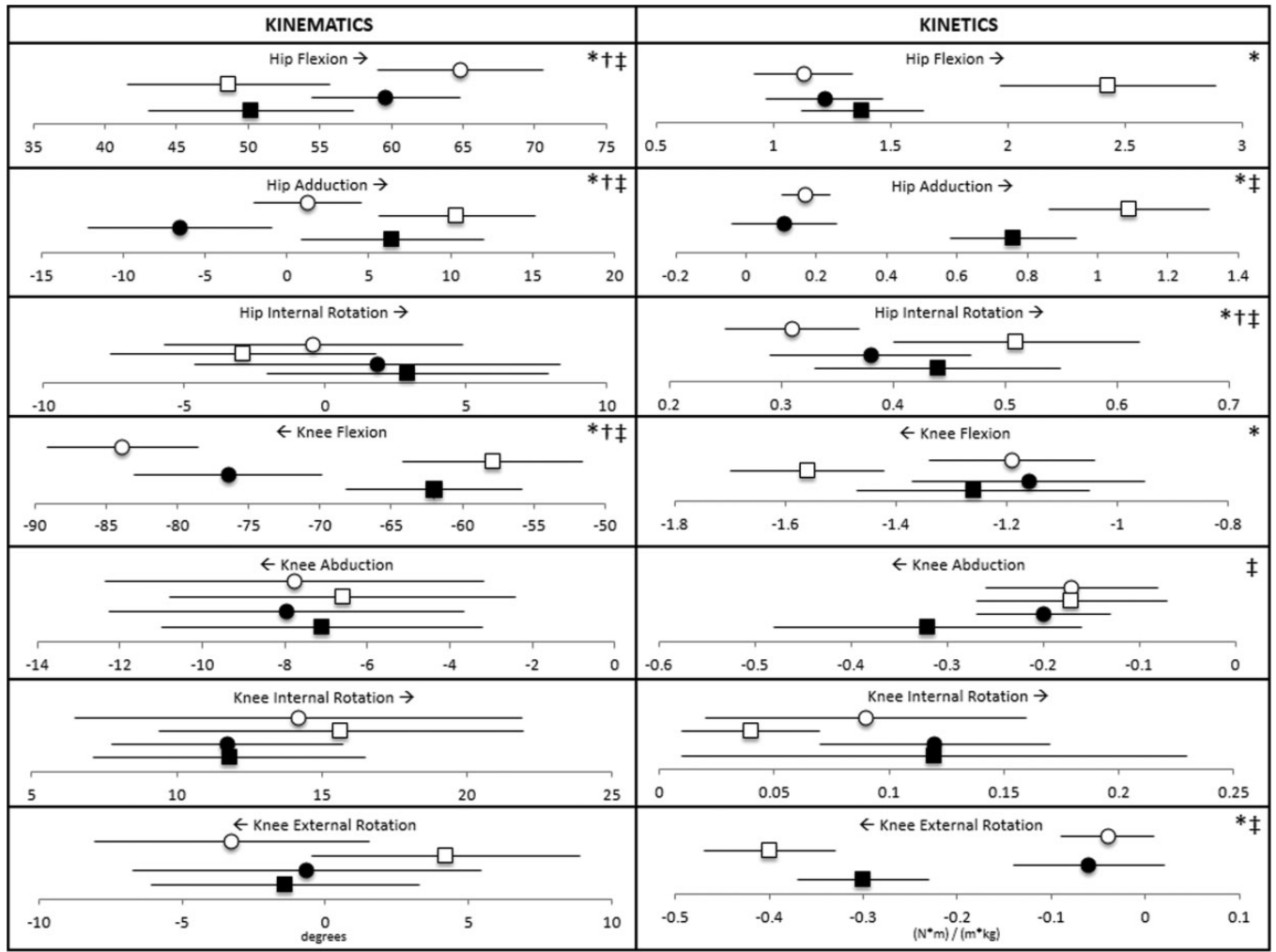


Figure 2. Means and standard deviations of hip and knee kinematics and kinetics during the SAG_{DL} (white circle), SAG_{SL} (white square), FRONT_{DL} (black circle), and FRONT_{SL} (black square) tasks. Biomechanics that were found to be significantly different ($P < .05$) compared with the SAG_{DL} task are identified by: *SAG_{SL}, †FRONT_{DL}, and ‡FRONT_{SL}. DL, double leg; FRONT, frontal plane; SAG, sagittal plane; SL, single leg.

flexion (R^2 , 0.12), hip internal rotation (R^2 , 0.11), knee flexion (R^2 , 0.23), knee internal rotation (R^2 , 0.02), and knee external rotation (R^2 , 0.08) moments were not predictive between tasks ($P > .05$).

DISCUSSION

Standard biomechanical assessments when screening for ACL injury risk and the effectiveness of ACL injury prevention programs typically use double-leg landings in the sagittal plane.^{31,33} However, most ACL injuries occur during unilateral foot contact in multidirectional sports that require frequent movements outside the sagittal plane.^{4,19} This study compared lower extremity biomechanics during double- and single-leg landings in the sagittal and frontal planes. As expected, each task elicited distinct biomechanics, indicating that both planes of movement and landing base of support may influence overall movement strategies

and the forces imposed on the hip and knee joints. Specifically, compared with the SAG_{DL} task, all other tasks resulted in more rigid landings with less hip and knee flexion. Additionally, single-leg tasks elicited the greatest joint moments, and jump landings after frontal plane movements elicited more predominant signs of dynamic lower extremity valgus, including greater hip adduction motion and hip adduction, hip internal rotation, knee abduction, and knee external rotation moments. Additionally, SAG_{DL} lower limb biomechanics were not always representative of lower limb biomechanics exhibited during other landing tasks, particularly the single-leg landings. Thus, in isolation, double-leg sagittal plane broad jump landing tasks may not fully represent the biomechanical demands of multidirectional sports, and therefore, further investigation into the inclusion of frontal plane and single-leg landing tasks to complement standard double-leg sagittal plane tasks in the assessment of high-risk lower extremity biomechanics may be warranted.

TABLE 2
Linear Regression Results (R^2) of the
Biomechanics Elicited During Double- and Single-Leg
Sagittal and Frontal Plane Tasks^a

	SAG _{DL} – SAG _{SL}	SAG _{DL} – FRONT _{DL}	SAG _{DL} – FRONT _{SL}	SAG _{SL} – FRONT _{SL}
Peak angle				
Hip flexion	0.07	0.46 ^b	0.08	0.61 ^b
Hip adduction	0.04	0.53 ^b	0.13	0.43 ^b
Hip internal rotation	0.26	0.42 ^b	0.21	0.40 ^b
Knee flexion	0.55 ^b	0.52 ^b	0.40 ^b	0.86 ^b
Knee abduction	0.52 ^b	0.83 ^b	0.58 ^b	0.89 ^b
Knee internal rotation	0.75 ^b	0.42 ^b	0.64 ^b	0.72 ^b
Knee external rotation	0.42 ^b	0.46 ^b	0.52 ^b	0.63 ^b
Peak moment, normalized				
Hip flexion	0.07	0.40 ^b	<0.001	0.12
Hip adduction	0.08	0.44 ^b	0.03	0.40 ^b
Hip internal rotation	0.002	0.37 ^b	0.27 ^b	0.11
Knee flexion	0.42 ^b	0.67 ^b	0.40 ^b	0.23
Knee abduction	0.23	0.54 ^b	0.05	<0.001
Knee internal rotation	0.02	0.60 ^b	0.26 ^b	0.02
Knee external rotation	0.11	0.50 ^b	0.001	0.08

^aDL, double leg; FRONT, frontal plane; SAG, sagittal plane; SL, single leg.

^b $P < .05$.

Our findings are in agreement with recent studies by Jones et al²¹ and Kristianslund and Krosshaug²³ who compared double-leg landings with sidestep cutting and pivoting tasks. Both groups reported moderate relationships of peak knee abduction angles between tasks yet the magnitude of knee abduction moments were largely unrelated.^{21,23} Similarly, we found that SAG_{DL} was predictive of knee kinematics during all other tasks yet was not representative of hip kinematics or hip or knee moments, especially when comparing double- with single-leg landing tasks. These differences at the hip are important because the position and forces at the hip are related to joint position and forces at the knee during closed chain activities.²⁰ Additionally, dynamic lower extremity valgus is characterized by high levels of hip adduction and internal rotation that correspondingly put the knee in positions of abduction and external rotation.³⁹ Because the landing biomechanics elicited during double-leg sagittal plane broad jump are not representative of biomechanics during more multidirectional sport-specific activities, further study regarding single-leg and multidirectional tasks that may complement standard screening tasks is warranted.

The largest biomechanical differences between tasks were observed when comparing double- and single-leg tasks. The joint angles and moments seen during single-leg landings appear to be more indicative of injurious positions reported during observational video analysis.^{4,18,22,24}

Moreover, hip kinematics and lower extremity moments employed during standard double-leg tasks were not predictive of the biomechanics used to perform the single-leg sagittal plane landing task. Specifically, biomechanical demands, especially joint moments, were greater during single-leg than double-leg activities, which may be due to the higher musculature demands needed to dissipate energy when landing on a single leg. More specifically, during a single-leg landing, large demands are required of the posterolateral hip musculature to maintain a level pelvis and prevent excessive hip adduction and internal rotation (components of dynamic lower extremity valgus). This was apparent in our results, as single-leg landings produced external hip flexion and adduction moments that were 2.2 and 6.6 times higher, respectively, than during double-leg landings. Harty et al¹⁴ previously reported similar differences in hip flexion and adduction moments between a single-leg landing and drop vertical jump landing. Considering that over 70% of ACL injuries occur during unilateral foot contact and the significantly greater forces generated during single-leg movements, our results highlight the eccentric demands of the posterolateral hip musculature during the deceleratory phase of single-leg landings. Thus, the greater forces exerted and larger demands of the hip musculature during the more challenging tasks may elucidate high-risk movement patterns not observed during more balanced and stable double-leg landings.

Despite the prevalence of ACL injuries and the higher biomechanical demands during unilateral foot contact, injury risk screening protocols have traditionally been performed with double-leg landing tasks. Hewett et al¹⁶ were able to identify at-risk female athletes with 78% sensitivity and 73% specificity based on knee abduction moments measured during a vertical drop-jump task. Other estimates of knee abduction moments during double-leg landing tasks using more clinically accessible measures have yet to predict knee injuries.¹³ Similarly, the Landing Error Scoring System (LESS) was developed as a clinically accessible screening tool to assess biomechanical faults during double-leg landing movements,³⁴ yet the success of the LESS to prospectively identify at-risk individuals has been mixed.^{34,43} Though discrepancies in prospective screening study results may be explained by the precision and validity of the technology (3- vs 2-dimensional analysis), it is also possible that the biomechanics obtained during an isolated double-leg sagittal plane task may not provide a comprehensive representation of injury risk in multidirectional athletes during more challenging single-leg and/or non-sagittal plane movements.

Additionally, the effectiveness of ACL injury prevention programs in modifying high-risk biomechanics are also conventionally studied using double-leg sagittal plane landings. Research indicates that most programs effectively modify components of dynamic lower extremity valgus as well as promote deeper knee and hip flexion angles during a double-leg sagittal plane landing after training.^{25,26} However, there is limited evidence as to whether prevention programs modify lower extremity biomechanics during single-leg or non-sagittal plane jump landings. Brown et al⁶ measured lower extremity biomechanics after standard

neuromuscular, plyometric, and core training programs during a double-leg sagittal plane and single-leg landing where participants were asked to transition from the sagittal to frontal plane. Regardless of the type of preventive training, participants showed no significant improvements in lower extremity biomechanics after training during the single-leg multiplanar hop yet considerable improvements during the double-leg sagittal plane task.⁶ This may suggest that either (1) double-leg sagittal plane tasks may not provide a comprehensive representation of potentially high-risk biomechanics during all sport-related movements and/or (2) ACL injury prevention programs place emphasis on double-leg sagittal plane landings and do not provide the appropriate stimulus to modify biomechanics during multidirectional and single-leg sports activities. This could help explain why ACL injury prevention programs are less effective in sports with higher single-leg and frontal plane demands.^{30,37} However, it is important to note that there is not yet any evidence to suggest that biomechanics that are high-risk during a double-leg sagittal plane tasks should be considered high risk during other tasks. Thus, future work needs to be performed to understand the extent to which single-leg sagittal and frontal plane tasks may help identify individuals at future risk of injury.

Limitations

While this study reports significant differences in the biomechanics employed during a variety of jump landings, caution should be used in implementing these tasks for screening ACL injury risk because none of the tasks used in this study have been evaluated as a tool to predict injury risk. These tests were performed on recreational athletes in a controlled laboratory environment that may not be entirely indicative of the environment (surface, perturbations), intensity (recreational vs competitive athletes), or sport demands (complex multiplanar movements) during game situations. Future studies may attempt to quantify the effects of combining movement planes on lower extremity biomechanics in more high-level athletes, considering that ability level may affect movement mechanics. Additionally, only the preferred stance limb was analyzed in this study. While there is some evidence to suggest that most injuries occur to the stance limb,⁵ analysis of both limbs and their symmetry indices may provide more clarity. Furthermore, analysis of frontal plane tasks was limited to the laterally moving limb. Neither the medially directed trail leg of the FRONT_{DL} task nor a medially directed single-leg landing was included in the analysis. Because these movements are also representative of the demands of multidirectional sports, they too should be analyzed in the future to further elucidate the effects of frontal plane moments on high-risk hip and knee biomechanics.

CONCLUSION

Standard assessment methods for examining ACL injury risk and the effectiveness of ACL prevention programs that emphasize lower extremity biomechanics during double-leg

landings in the sagittal plane may not provide a comprehensive representation of the lower extremity biomechanics that are employed during sport activities. Based on our results, further investigation into the inclusion of single-leg and frontal plane jump landing tasks as complements to traditional double-leg sagittal plane tasks for the assessment of lower extremity biomechanics of athletes who participate in multidirectional sports is warranted.

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