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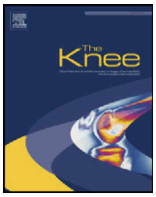

Biomechanical and neuromuscular comparison of single- and multi-planar jump tests and a side-cutting maneuver: Implications for ACL injury risk assessment

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ABSTRACT

Background: Non-contact anterior cruciate ligament (ACL) injuries are a major problem among adolescent female soccer and handball players. Therefore, the aim of this study was to examine if known biomechanical and neuromuscular ACL injury risk factors obtained from single-planar jump-landings and multi-planar side-jumps can resemble the demands of side-cutting maneuvers, a known high-risk ACL injury movement for this population.

Methods: Twenty-four female soccer and handball players (mean ± SD: age: 17 ± 1 year; height: 172 ± 66 cm; mass: 67 ± 9 kg) performed a series of functional tasks including two single-planar jump-landings, two multi-planar side-jumps and a sports-specific side-cutting maneuver on their dominant leg. Frontal and sagittal plane knee and hip joint kinematics and kinetics were calculated from three-dimensional motion analysis, whereas hamstring and quadriceps muscle pre-activity levels were measured with surface electromyography.

Results: The sports-specific side-cut was distinguished by more knee flexion at initial contact, greater abduction angles and external knee abduction moments, higher biceps femoris and semitendinosus muscle pre-activity levels than both the single-planar jump-landings and multi-planar side-jumps ($p < .05$). Whilst, poor-to-strong spearman rank correlation coefficients inconsistently were found for the biomechanical and neuromuscular ACL injury risk factors explored between the side-cut and the single-planar jump-landings ($r_s = 0.01–0.78$) and multi-planar side-jumps ($r_s = 0.03–0.88$) respectively.

Conclusion: Single-planar jump-landings and multi-planar side-jumps should be used with caution to test for non-contact ACL injury risk factors in adolescent female soccer and handball players, because they do not mimic the biomechanical nor neuromuscular demands of the most frequent injury situation.

1. Introduction

Non-contact anterior cruciate ligament (ACL) injuries remain a serious problem among female athletes participating in team sports [1,2]. In fact, the incidence of non-contact ACL injuries is three to five times higher for female athletes compared to their male counterparts [1,3,4], and particularly the adolescent females (between 14 and 19 years) are at high risk of non-

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contact ACL injuries [2,5]. In team sports, non-contact ACL injuries often occur during abrupt decelerations, change in directions, and single-leg landings [6–8], and in both soccer and handball, the majority of non-contact ACL injuries occurs when players perform lateral change in directions (side-cutting maneuvers) [9,10]. Therefore, ACL injury research has focused on establishing both biomechanical and neuromuscular ACL injury risk factors. Information that on the one hand can be used to develop effective screening test protocols to identify athletes at increased risk of future injuries [11–13]. And on the other hand, to design effective injury prevention programs, as research indicate that both biomechanical and neuromuscular ACL injury risk factors are modifiable trough training interventions [14–17].

The mechanism of non-contact ACL injuries is multi-factorial, and likely includes both hormonal, anatomical, biomechanical and neuromuscular factors [18,19]. Nevertheless, large prospective studies on young female athletes [11,20] have demonstrated that biomechanical mechanisms such as landing with a more extended knee, increased abduction knee angle at initial contact (IC), and increased knee abduction angles and moments are all associated with increased ACL injury risk. Moreover, computer model analysis has indicated that the combination of landing/cutting with more extended hip and knee joint angles elevate anterior tibial shear forces, which most likely result in increased strain in the ACL [21,22]. In contrast, greater hip flexion at IC has previously been associated with greater peak external knee abduction moments during side-cutting [23]. In addition, the neuromuscular activation patterns of the hamstring muscles are important for dynamic knee control in both the sagittal and frontal plane [24,25], and have similarly been associated with increased ACL injury risk [13,26]. In fact, a study by Zebis et al. found that adult female handball and soccer players with reduced pre-activation (0–10 ms prior to IC) in the m. semitendinosus (ST) muscle and increased vastus lateralis (VL) pre-activity during a sport specific side-cutting maneuver were at high risk of sustaining a future non-contact ligament injury [13]. Screening players for the aforementioned biomechanical and neuromuscular ACL injury risk factors is therefore a common practice in both clinical and field settings to identify players with increased risk of sustaining future ACL injuries [11,27].

When screening players for ACL injury risk factors, it is essential that the biomechanical and neuromuscular demands of the screening tests employed are representative of the demands experienced during high-risk injury situations such as side-cutting. Side-cutting maneuvers are multi-planar movements that include a deceleration of the players' body followed by a rapid change of direction, during which the knee joint is exposed to high loads [28]. Nevertheless, single-planar bilateral vertical drop jump remains one of the most commonly used tests to assess for ACL injury risk factors among team sport athletes [11,12,20,29]. Even though large prospective studies have found contradictory results when bilateral vertical drop jumps were used to identify team sport players at increased risk of ACL injuries based on biomechanical risk factors [11,20,27,28] and neuromuscular hamstring activity patterns [26]. Unilateral jump tests, such as single-leg landings, single-leg drop vertical jumps, and single-leg horizontal jumps are also widely used to simulate the initial landing and deceleration phase experienced during high-risk injury situations [30–32]. Given the high prevalence of non-contact ACL injuries in soccer and handball [9,10] and because existing literature has shown that single-leg jump tests do not resemble the magnitude of the biomechanical loads (e.g. knee and hip abduction joint angles and moments) [31,32] and nor the neuromuscular activity (hamstring pre-activity) [30] players experience during side-cutting maneuvers. Simultaneously, standardized jump tests including an abrupt and explosive change of direction might be a better alternative to resemble the knee loads of side-cutting.

The literature comparing ACL risk factors obtained from side-cutting with those of multi-planar jump tests, with a lateral side-jump component, is however very limited. A study by O'Connor et al. found poor relationships in frontal plane knee kinematics and kinetics between unanticipated side-cutting and unilateral multi-planar jump landing tasks (with varying forward jump length and vertical drop height) involving a lateral side-jump after initial landing [33]. It does however still remain largely unexplored if multi-planar jump tasks, with a change of direction component, more closely resemble the demands placed on the knee during sports-specific side-cutting in adolescent females. Such standardized tests might be preferred over side-cutting tests in large prospective studies, or in clinical and applied field settings, because they are easier to standardize and less time-consuming.

The aim of this study was therefore to examine if known biomechanical and neuromuscular ACL injury risk factors obtained from standardized single-planar jump-landing and multi-planar side-jump tests can resemble the biomechanical and neuromuscular demand experience during a sports-specific side-cutting maneuver. We hypothesized that the side-cutting maneuver would be associated with higher biomechanical and neuromuscular demands compared to both the single-planar jump-landing and multi-planar side-jump tasks. Moreover, the multi-planar side-jump tasks, due to their multidirectional movement similarities with the side-cutting maneuver, were expected to more closely resemble the high knee abduction moments and increased hamstring muscle pre-active levels experienced during side-cutting.

2. Methods

2.1. Participants & test protocol

Twenty-four elite adolescent female handball (n = 13) and soccer (n = 11) players (age: 17 ± 1 year; height: 172 ± 66 cm; mass: 67 ± 9 kg), without any history of lower-limb musculoskeletal injuries 12 months prior to testing, volunteered to participate in this study. All participants and their parents were informed about the purpose and content of the project, and with their parent's informed consent, all agreed to participate in this study in accordance with The Declaration of Helsinki. The study was approved by the local ethics committee (H-17003542).

The participants attended a single test session in a clinical 3D motion analysis laboratory. The test protocol consisted of four procedures: 1) motion capture marker and surface electromyography (EMG) electrode placements; 2) a standardized five-minute

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warm-up routine; 3) maximum voluntary muscle contraction (MVC) tests of the knee flexor and extensor muscles; and 4) five functional tests, performed in a randomized order, consisting of two single-planar jump-landing tests, two multi-planar side-jump tests, and a sports-specific side-cutting maneuver.

2.2. Kinematic and kinetic measurements

Three-dimensional lower-body kinematics were recorded at 250 Hz using an eight-camera motion capture system (T40 cameras, Vicon motion systems Ltd., Oxford, UK) and a modified Helen Hayes marker set-up as previously described in Bencke et al. [34]. Three-dimensional ground reaction force data were recorded simultaneously at 1000 Hz with an AMTI force platform (OR6-7, AMTI, Massachusetts, USA). Using inherent Vicon plug-in-git software (Nexus 2.7, Vicon motion systems Ltd., Oxford, UK), kinematic marker data were filtered with a Woltering cubic spline filter [35], with a predicted mean square error of 10 mm. Simultaneously, ground reaction force data were filtered with a 50 Hz low-pass Butterworth filter, before hip and knee joint angles and net moments were calculated. IC was identified as the time when the vertical ground reaction force data crossed a 10 N threshold.

2.3. EMG measurements

Neuromuscular activity was measured from m. biceps femoris long head (BF), m. semitendinosus (ST) and m. vastus lateralis (VL) of the participants' preferred push-off leg. EMG electrodes, with 2.0 cm inter-electrode distance (Ambu® Blue Sensor N ECG, Ballerup, Denmark), were placed over the muscle belly and aligned with muscle fibers to reduce cross-talk, as recommended by the SENIAM guidelines [36]. All electrode locations were shaved and cleaned with ethanol to ensure minimal skin impedance [37], whilst tape was used to fix the EMG-electrodes to reduce movement artifacts from the wires. The EMG signals were pre-amplified, band-pass filtered (five to 450 Hz) and sampled at 1000 Hz (16-bit). The digitized EMG recordings were high-pass filtered at a cut-off frequency of 10 Hz.

2.4. Maximum voluntary contraction protocol

Maximum EMG activity was obtained as previously described in Husted et al. [30], with the participants performing a four-second maximal isometric knee flexor contraction to record MVC of the BF and ST muscles. Whilst the participants performed a four-second maximal isometric knee extensor contraction to record MVC of the VL muscle. Three MVC trials were performed for each muscle with a 30-s rest period between each trial to avoid fatigue, and strong verbal encouragement was given to the participants in all MVC trials.

2.5. Functional tests

The participants completed two single-planar jump-landing tests: a single-leg landing (SLL) and a single-leg drop-landing (SLDL); two multi-planar side-jump tests: a single-leg side-jump (SLSJ) and a single-leg drop-side-jump (SLDSJ). The jump onto the force plate was systematically changed from a horizontal forward jump to a horizontal forward drop jump to increase the intensity within both jump tasks (Figure 1); and a sport-specific side cutting maneuver (Side-Cut) [30,34]. The participants completed the tests on their dominant leg, defined as the leg opposite to the preferred throwing arm or kicking leg [14]. The single-planar jump-landing (SLL, SLDL) and multi-planar side-jump tests (SLSJ, SLDSJ) were repeated until three successful trials were recorded, whilst five successful trials were recorded for the Side-Cut.

For the SLL test, participants were positioned in front of the force plate at a distance corresponding to 80% of their own leg length (measured from ASIS to the medial malleolus). From this position, the participants were instructed to perform a single-leg horizontal forward jump onto the force plate. For the SLDL test, the participants were initially positioned on a 35 cm high wooden box at a distance corresponding to 80% of their own leg length in front of the force plate. From the initial start position, the participants were instructed to perform a single-leg vertical drop jump. For both the SLL and SLDL tests, participants were instructed to land on their push-off leg and maintain their balance for three seconds after the initial landing.

For the multi-planar SLSJ test, participants were positioned diagonally in front of the force plate at a distance corresponding to 80% of their own leg length (measured from ASIS to the medial malleolus) in front of the force plate, and 50% of their leg length to the side of the force plate (Figure 1). From this position, participants were instructed to perform a single-leg diagonal forward jump onto a force plate, and immediately upon landing (on their push-off leg) perform a maximal lateral side-jump (change of direction). Participants were instructed to perform the lateral side-jump to the opposite side of their push-off leg (e.g. lateral side-jump to the right side for participants landing on their left leg). For the SLDSJ test, the participants were initially positioned on a 20 cm high wooden box diagonally in front of the force plate. The wooden box was placed at a distance corresponding to 80% of the participants' leg length in front of the force plate, and 50% of their leg length to the side of the force plate. From this position, participants were instructed to perform a single-leg drop jump onto the force plate and immediately upon landing perform a maximal lateral side-jump to the opposite side of their push-off leg. For both the SLSJ and SLDSJ, trials were excluded, and the participants were asked to repeat the trials if they landed with their foot placed more than 10 cm in front of the force plate (indicated by a line of tape).

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Figure 1. Frontal plane view of the five functional tests performed in this study. The two single-planar jump tests: single-leg landing (SLL) and single-leg drop-landing (SLDL), the two multi-planar jump tests: single-leg side-jump (SLSJ) and single-leg drop-side-jump (SLDSJ), and the sports-specific side-cutting maneuver (Side-Cut).

For the Side-Cut, participants were positioned four to five meters in front of the force plate and instructed to perform a forceful side-cut in front of a fictive opponent, similar to a match situation. To best simulate the individual performance like in a match situation, we did not predefine a cutting angle or use a pre-set running speed [30,34].

2.6. Data processing

Since the risk of ACL injury is highest during the initial contact phase, only the initial 100 ms of the contact phase was used for the analysis of kinematic and kinetic parameters [6,38]. Sagittal and frontal knee and hip joint angles at IC, peak abduction knee joint angle, along with local maxima of the external knee and hip flexion and abduction joint moments were obtained for each trial.

Following root-mean-square (RMS) smoothening of the EMG signals, with a window of 30 ms and 29 ms overlap, the average RMS EMG signal amplitude recorded in the 10-ms time interval leading up to IC was calculated for each trial [13]. The RMS EMG-signal amplitudes recorded from each trial were normalized to the individual participant's maximum RMS EMG amplitude recorded during the MVC tests. Average neuromuscular pre-activity of the 10-ms time interval immediately prior to IC was calculated for the normalized BF, ST and VL RMS EMG amplitude [13,14,30]. Additionally, the VL-ST difference was calculated by

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subtracting the mean normalized ST pre-activity from the corresponding pre-activity in the VL muscle for the individual trials as previously described in Zebis et al. [13].

2.7. Statistical analysis

The averages of the three trials for the jump tests (SLL, SLDL, SLSJ, SLDSJ) and five trials for the Side-Cut were calculated for each participant and used for the statistical analysis. All biomechanical and neuromuscular parameters were normally distributed (Shapiro–Wilk: $p > .05$). A one-way repeated-measures analysis of variance (ANOVA) were used to test if the biomechanical and neuromuscular ACL injury risk factors were influenced by the functional test employed. Pairwise post-hoc comparisons, with Bonferroni corrections, were used to determine differences in the measured ACL injury risk factors between the individual tests. Furthermore, Spearman rank correlation analysis (r_s) was used to calculate correlation coefficients between the Side-Cut and the individual jump tests. The following values were used to distinguish the levels of correlation, 0.00 to 0.25 (no or poor relationship), 0.25 to 0.50 (low-to-moderate relationship), 0.50 to 0.75 (moderate-to-strong relationship) and above 0.75 (strong-to-excellent relationship) [39]. The statistical analysis was performed in the Statistical Package for the Social Sciences software (version 22.0, SPSS Inc. Chicago, IL, USA) with the alpha level set at ≤0.05. One participant was unable to perform the two multi-planar side-jump tests (SLSJ and SLDSJ), hence the statistical analysis of those tests only include data from 23 participants.

3. Results

3.1. Biomechanical risk factors

The one-way repeated ANOVA revealed that all knee and hip parameters were significantly affected by the functional test employed (Table 1). Furthermore, the post-hoc analysis revealed that the participants landed with significantly higher knee flexion angles at IC (mean difference between 5.2 and 9.6 deg., $p < .005$) and had significantly higher peak external knee abductions moments (mean difference between 0.30 and 0.61 Nm/kg BM, $p < .05$) during the Side-Cut compared to the four jump tests (Figure 2). Moreover, the comparison revealed that the participant had significantly greater peak knee abduction angles during the Side-Cut, compared to the two single-planar jump-landing tests (SLL and SLDL) and the OLDSJ (mean difference between 1.53 and 3.86 deg., $p < .02$). Moreover, significantly higher knee adduction joint angles at IC were observed for the two single-planar jump-landing tests (SLL and SLDL) compared to the Side-Cut (mean difference between 1.57 and 1.64 deg., $p < .01$). Finally, significantly moderate-to-excellent correlations were observed between the Side-Cut and the four jump tests for the knee adduction joint angles at IC (r_s between 0.68 and 0.85), whilst low-to-moderate correlations generally were observed for the knee flexion angle at IC, peak external knee flexion and abduction moments (Figure 2).

Inconsistent differences were observed for the hip joint parameters between the Side-Cut and the four jump tests (Figure 3). Nevertheless, the post-hoc analysis revealed that the participants landed with significantly higher hip flexion angles at IC (mean difference of 11.26°, $p < .01$) and had significantly lower peak external hip flexion moments (mean difference of 1.49 Nm/kg BM, $p < .05$) during the Side-Cut compared to the OLDL jump test. Whilst significantly greater hip adduction joint angles at IC (mean difference of 6.97 deg., $p < .01$) and peak external hip abduction moments (mean difference of (0.80 Nm/kg BM, $p < .05$) were observed for the Side-Cut compared to the OLJ jump test. Finally, poor to moderate correlations were observed between the Side-Cut and the four jump tests for the hip joint parameters (Figure 3).

Table 1
ANOVA main effects on the selected biomechanical and neuromuscular ACL injury risk factors.

ACL injury risk factors	$F_{(4,\ 88)}$	p
Biomechanical		
Knee flexion angle at IC	39.4	<0.001*
Peak knee flexion moment	3.3	0.037*
Knee adduction angle at IC	16.3	<0.001*
Peak knee abduction/adduction angle	27.3	<0.001*
Peak knee adduction moment	23.0	<0.001*
Hip flexion angle at IC	21.1	<0.001*
Peak hip flexion moment	9.5	<0.001*
Hip adduction angle at IC	13.2	<0.001*
Peak hip abduction moment	10.2	<0.001*
Neuromuscular		
BF pre-activity	11.4	<0.001*
ST pre-activity	15.1	<0.001*
VL pre-activity	0.7	0.536
VL_ST_Diff pre-activity	5.6	0.002*

* Denotes significant main affect ($p \le .05$).

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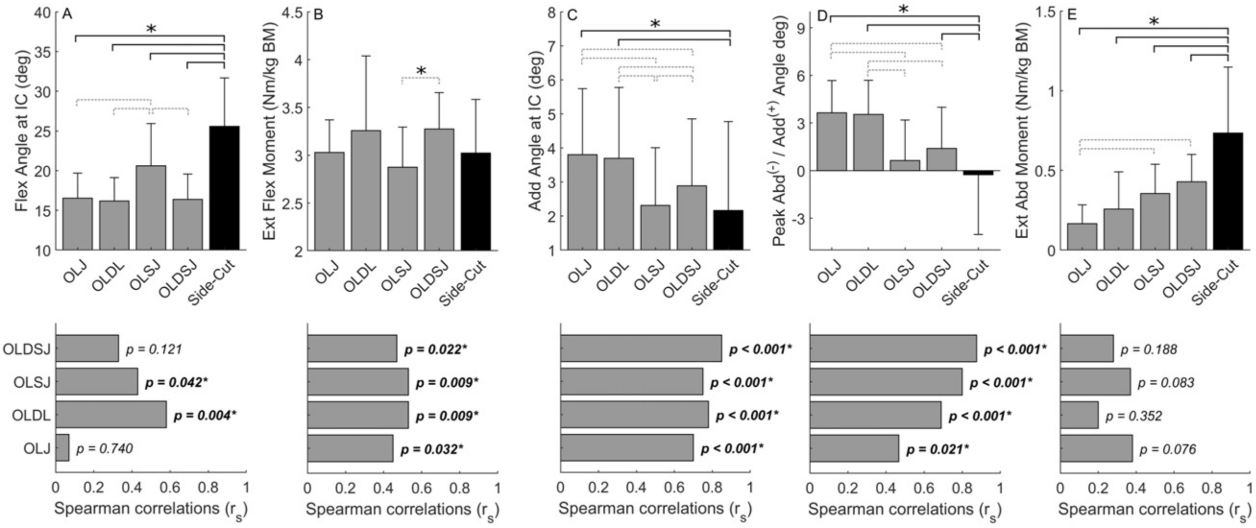

Figure 2. The top panel display mean ± SD and post-hoc comparisons for knee flexion angle at IC (A), peak external knee flexion moment (B), knee adduction angle at IC (C), peak knee abduction angle (D), and peak external knee abduction moment (E). The horizontal black brackets indicate significantly pairwise differences between the Side-Cut and jump tests, whilst the horizontal dotted gray brackets indicate significantly pairwise differences between the individual jump tests. The bottom panel display spearman rank correlations (r_s and *p-values*) between the Side-Cut and the individual the jump tests. * indicates significant difference or correlation ($p \leq .05$).

3.2. Neuromuscular risk factors

The pre-activity level of the BF, ST, and the VL-ST difference was all significantly affected by the functional test employed (Table 1). The post-hoc analysis revealed that the participants had significantly higher ST pre-activity level during the Side-Cut compared to the four jump tests (mean difference between nine and 19%MVC, $p < .05$). Significantly higher BF pre-activation was observed for the Side-Cut (mean difference between 8 and 12 %MVC, $p < .01$) compared to the SLL, SLDL and SLSJ (Figure 4). Moreover, significantly lower VL-ST difference was observed for the SLDL (mean difference 17 %MVC, $p = .024$), compared to the Side-Cut. Finally, the SLSJ test demonstrated moderate correlations (r_s between 0.48 and 0.59) with the Side-Cut for all neuromuscular pre-activation parameters, whereas low-to-moderate correlations generally were observed between the Side-Cut and the other jump tests (SLL, SLDL and SLDSJ).

4. Discussion

The aim of this study was to examine if known biomechanical and neuromuscular ACL injury risk factors obtained from single-planar jump-landing and multi-planar side-jump tests can resemble the demands of a sports-specific side-cutting maneuver, a known high-risk movement for adolescent female soccer and handball players. Neither the single-planar jump-landing tests (SLL, SLDL), nor the multi-planar side-jump tests (SLSJ, SLDSJ) were able to resemble the magnitudes of the biomechanical knee and hip joint loading or neuromuscular hamstring and quadriceps muscle activity of the sports-specific side-cutting maneuver. Furthermore, low-to-moderate correlations were generally observed between the side-cutting maneuver and all jump tests. The four jump tests particularly underestimated the knee flexion angle at IC, peak knee abduction angle and peak external knee abduction moments during the initial contact phase, and BF and ST muscle pre-activity levels adolescent female experience during the high-risk side-cutting maneuver.

The results of this study is in line with previous studies and support the notion that standardized unilateral single- or multi-planar jump tests do not resemble the knee joint loading experienced during sports-specific side cutting [30] or more standardized planned [31] and unplanned sidestepping [32,33]. Together, these results indicate that the movement patterns of simple jump tests deviate from the unique movement pattern of side-cutting. During the Side-Cut, the participants landed with a more flexed knee at IC compared to the four jump tests. Landing with a more flexed knee is believed to reduce the anterior shear forces in the knee joint compared to landing with a more extended knee [18]. On the other hand, peak external knee flexion moments did not differ between the side-cutting maneuver and the four jump tests, indicating that the anterior shear forces may not differ among the function tests explored in this study. In contrast, higher peak external knee abduction moments were observed within the first 100 ms after initial landing of the Side-Cut compared to the four jump tests, indicating that the stresses on the ACL were highest during the Side-Cut [18]. Greater hip flexion at IC has previously been associated with greater peak external knee abduction moments during side-cutting [23]. Nevertheless, greater hip flexion angles at IC was not systematically observed for the Side-Cut compared to the four jump tests and therefore cannot explain the greater external knee abduction moments observed for the Side-Cut. The results from this study therefore indicate that simple jump tests, in particular, cannot

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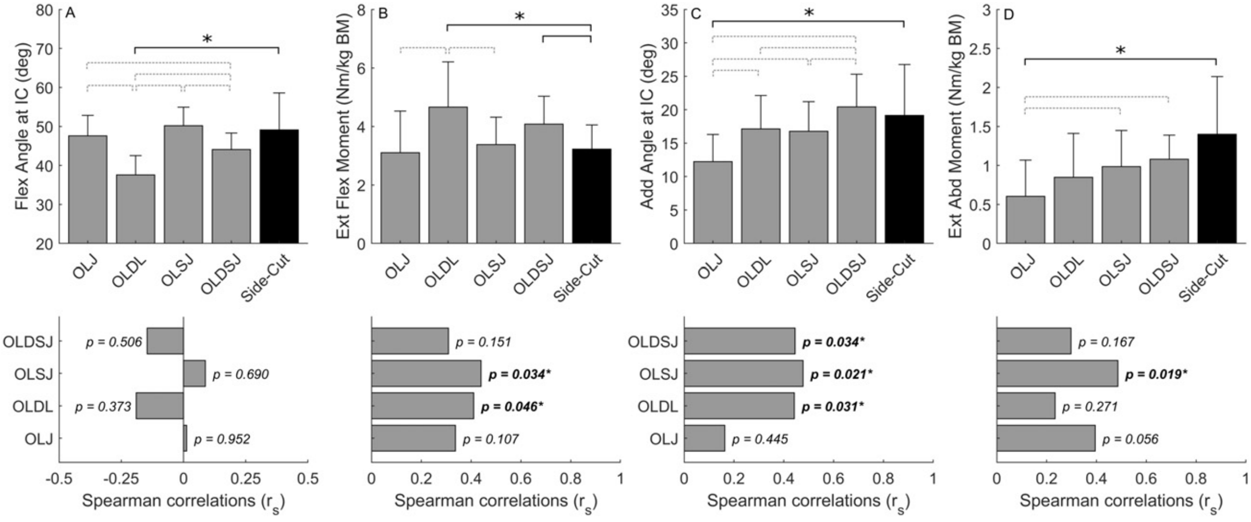

Figure 3. The top panel display mean ± SD and post-hoc comparisons for hip flexion angle at IC (A), peak external hip flexion moment (B), hip adduction angle at IC (C), and peak external hip abduction moment (D). The horizontal black brackets indicate significantly pairwise differences between the Side-Cut and jump tests, whilst the horizontal dotted gray brackets indicate significantly pairwise differences between the individual jump tests. The bottom panel display spearman rank correlations (r_s and *p-values*) between the Side-Cut and the individual the jump tests. * indicates significant difference or correlation ($p \leq .05$).

mimic the high frontal plane knee joint load associated with increased risk of knee injuries [11] athletes experienced during sport-specific side-cutting maneuvers. This would further imply that the commonly used unilateral jump tests, to identify biomechanical ACL injury risk factors in adolescent female team sports players should be used with caution.

The hamstring muscle group is important for dynamic knee joint control, because they counteract the external knee moments in both the sagittal and frontal plane [24,25]. During the side-cutting maneuver, participants increased both the pre-activity levels of the BF and ST muscles to counteract and protect the knee against the high peak external abduction moments. The higher BF and ST muscle pre-activity levels observed for the Side-Cut, and low-to-moderate correlations between tasks observed in this study are in agreement with the previous findings by Husted et al. [30]. In contrast to the study by Husted et al. [30], a multi-planar side-jump test was included in this study to better simulate the multidirectional change of direction component of the high-risk side-cutting maneuver. Though the inclusion of a lateral side-jump immediately after initial landing resulted in higher knee abduction angles, external knee abduction moments, and increased BF and ST muscle pre-activity levels, it could not fully

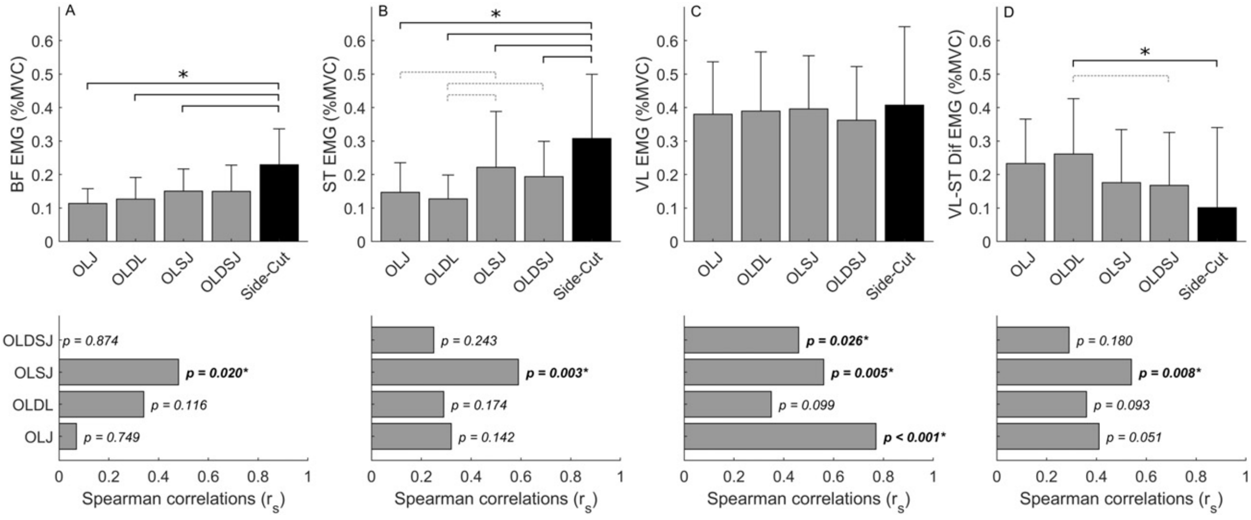

Figure 4. The top panel display mean ± SD and post-hoc comparisons for the neuromuscular pre-activity level, normalized to MVC, for BF (A), ST (B), VL (C) and VL-ST difference (D). The horizontal black brackets indicate significantly pairwise differences between the Side-Cut and jump tests, whilst the horizontal dotted gray brackets indicate significantly pairwise differences between the individual jump tests. The bottom panel display spearman rank correlations (r_s and *p-values*) between the Side-Cut and the individual the jump tests. * indicates significant difference or correlation ($p \leq .05$).

mimic the demands of the Side-Cut. Thus, the findings of the present study indicate that the ST muscle pre-activity measured during single-planar jump-landing and multi-planar side-jump tests may not be generalizable to side-cutting movements. Therefore, practitioners and clinicians should be aware that standardized jump tests, similar to those explored in this study, is not suitable to identify adolescent female soccer and handball players with reduced ability to activate the hamstring muscles during side-cutting movements.

The higher peak knee external abduction moments and associated increase in the medial hamstring muscle (m. semitendinosus) pre-activity levels, observed during the side-cutting maneuver, might be a consequence of higher ground reaction force magnitudes or increased moment arm of the ground reaction force in the frontal plane or the combination of both [27,28]. The side-cutting maneuver was however associated with the lowest resultant ground reaction force magnitudes (2.90 ± 0.74 N/kg BW) compared to the four jump tests (between 3.11 ± 0.50 and 4.67 ± 0.61 N/kg BW). This may indicate that the higher peak external knee abduction moments observed during the side-cutting maneuver could be a consequence of an increased ground reaction force moment arm in the frontal plane. The increased peak dynamic knee valgus and higher hip abduction angle observed during the initial contact phase of the side-cutting maneuver in this study may as well have contributed to the higher peak knee external abduction moments [28,34]. Furthermore, the side-cutting maneuver is characterized by a wider foot position relative to the position of the knee, in comparison to the single-planar jump-landing tests in particular (Figure 1), which also may have contributed to the elevated knee external abduction moments [28].

Due to the multidirectional nature of the side-cutting maneuver, the multi-planar side-jump with a change of direction component was expected to better resemble the biomechanical and neuromuscular demands of the side-cutting maneuver. The inclusion of a lateral side-jump component significantly increased the knee abduction angle at IC, peak knee abduction angle and the peak external knee abduction moments in the initial contact phase, and elevated both the BF and ST pre-activation muscle activity compared to the two single-planar jump-landing tests. The change in jump approach angle, from a forward jump during the single-planar jumps to a diagonal forward jump during the multi-planar jumps, may as well have contributed to the higher biomechanical and neuromuscular demands observed for the multi-planar jump tests in this study [40,41]. These results indicate that both the biomechanical and neuromuscular demands of multi-planar side-jump tests are markedly different than those of single-planar jump-landing tests. Nevertheless, neither the single-planar jump tests nor the multi-planar side-jump tests can resemble the unique movement pattern and neuromuscular activity of sport-specific side-cutting maneuvers.

The jump task modification from a horizontal forward jump to a horizontal forward drop jump increased the knee and hip moments within both the single-planar jump-landing and multi-planar side-jump tests. The increase observed at a knee joint level is in contrast with results from O'Connor et al. that found no difference in knee sagittal plane moments, but similar to the present study, observed higher knee adduction moments in a forward side-jump compared to a box drop side-jump [33]. Despite the increase in both sagittal and frontal plane knee joint loading, when the jump tasks were modified from a horizontal forward jump to a horizontal forward drop jump, the BF muscle pre-activity remained largely unaffected in this study. On the other hand, pre-activity of the ST muscle was reduced within both the single-planar jump-landing and multi-planar side-jump tests. These results indicate that alterations from single- to multi-planar movements, and/or horizontal forward jump to horizontal forward drop jump movements can be used to gradually increase the biomechanical loads on the knee and hip joint when designing ACL preventions and rehabilitation programs. Furthermore, alterations from single- to multi-planar movement effectively can be used in such programs to increase the neuromuscular demands of the medial hamstring muscle (m. semitendinosus).

One limitation of this study may be that the subjects were not systematically trained to perform the different single-planar jump-landing and multi-planar side-jump tests, but only accustomed to the tests through a number of practice trials. Although they were skilled athletes it is possible that more practice may have increased the intensity of especially the multi-planar side-jump tests, and thus have increased the frontal plane dynamics. Moreover, this study was not a prospective study, and as such it may not be concluded that the examined jump tests would not be able to identify athletes at higher risk of sustaining an ACL injury, but the presented biomechanical characteristics do not suggest that the examined jump tests would be optimal for this purpose. This, however, may be investigated in future prospective studies. Whilst the main focus of the present study was on the knee joint biomechanics and neuromuscular activity patterns, we acknowledge that knee joint control is also influenced by hip joint biomechanics. Therefore, a limitation with the present study design is that hip joint muscle activity was not investigated. Moreover, the biomechanical differences observed in hip joint biomechanics between the functional tests explored may indicate that neuromuscular activity of the hip joint may yield interesting information, and should thus be included in future studies.

5. Conclusion

Neither the single-planar jump-landing nor the multi-planar side-jump tests examined in this study was able to mimic the high knee abduction angles, external knee abduction moments or neuromuscular hamstring pre-activity levels experienced during a sports-specific side-cutting maneuver. The present findings support the notion that caution should be taken when using standardized jump tests to identify adolescent female soccer and handball players with increased risk of a future non-contact ACL injury. As these tests cannot reproduce the biomechanical or neuromuscular demands of side-cutting maneuvers, a known high-risk movement for this population.

Declaration of competing interest

We hereby declare, that there was no conflict of interest associated with our submission of the manuscript entitled *"Biomechanical and neuromuscular comparison of single- and multi-planar jump tests and a side-cutting maneuver: Implications for ACL injury risk assessment"* for consideration in *The Knee*.

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