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Introducing a novel test with unanticipated medial/lateral diagonal hops that reliably captures hip and knee kinematics in healthy women

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ABSTRACT

Despite a vast literature on one-leg hops and cutting maneuvers assessing knee control pre/post-injury of the anterior cruciate ligament (ACL), comprehensive and reliable tests performed under unpredictable conditions are lacking. This study aimed to: (1) assess the feasibility of an innovative, knee-challenging, one-leg double-hop test consisting of a forward hop followed by a diagonal hop (45°) performed medially (UMDH) or laterally (ULDH) in an unanticipated manner; and (2) determine within- and between-session reliability for 3-dimensional hip and knee kinematics and kinetics of these tests. Twenty-two healthy women (22.3 ± 3.3 years) performed three successful UMDH and ULDH, twice 1–4 weeks apart. Hop success rate was 69–84%. Peak hip and knee angles demonstrated moderate to excellent within-session reliability (intraclass correlation coefficient [ICC] 95% confidence interval [CI]: 0.67–0.99, standard error of measurement [SEM] $\leq$ 3°) and poor to excellent between-session reliability (ICC CI: 0.22–0.94, SEM $\leq$ 3°) for UMDH and ULDH. The smallest real difference (SRD) was low ($\leq$ 5°) for nearly all peak angles. Peak hip and knee moments demonstrated poor to excellent reliability (ICC CI: 0–0.97) and, in general, moments were more reliable within-session (SEM $\leq$ 0.14 N.m/kg.m, both directions) than between-session (SRD $\leq$ 0.43 N.m/kg.m). Our novel test was feasible and, in most but not all cases, provided reliable angle estimates (within-session > between-session, both directions) albeit less reliable moments (within-session > between-session, both directions). The relatively large hip and knee movements in the frontal and transverse planes during the unanticipated hops suggest substantial challenge of dynamic knee control. Thus, the test seems appropriate for evaluating knee function during ACL injury rehabilitation.

1. Introduction

Around 3% of amateur athletes and 15% of elite athletes injure their anterior cruciate ligament (ACL) every year (Moses et al., 2012) and 70% of ACL injuries seem to occur in noncontact situations (Griffin et al., 2000). One-leg hop tests have been studied extensively in biomechanical research to assess risk of ACL re-injury, compare lower limb asymmetries between injured and uninjured sides in patients with a unilateral ACL injury, and determine progress in rehabilitation (Hegedus et al., 2015). Aberrant neuromotor control and lower limb biomechanics associated with one-leg landing and cutting maneuvers, might increase the risk of ACL (re)injury owing to altered loading of the knee (Brown et al., 2014; McLean et al., 2008). Non-contact ACL injuries commonly occur during the early deceleration phase of one-leg landing followed by a cutting maneuver (Besier et al., 2001b; Garrett and Yu, 2007; Griffin et al., 2000; Griffin et al., 2006). There might be some compensation between ipsi- and contra-lateral limbs while performing side- and cross-cutting maneuvers which might challenge between-limb comparisons for individuals with or without an ACL injury in laboratory-based studies. On the contrary, one-leg medial (Kea et al., 2001) and lateral (Vandermeulen et al., 2000) (diagonal) hops might mimic the forces occurring during side- and cross-cutting maneuvers respectively while enhancing between-limb comparisons.

To decrease (re)injury risk and successfully return to knee-demanding sports following knee injury, sportspeople should possess sufficient lower limb control during cutting and side-to-side maneuvers (Thomeé et al., 2011). Valid and reliable tests that evaluate lower limb control during such conditions are therefore required. To date, a few studies have investigated within- and/or between-session reliability of movement patterns during such tasks, and these are limited to side-cutting (Alenezi et al., 2016; Besier et al., 2001b; Marshall et al., 2014; Mok et al., 2017; Sankey et al., 2015). Excellent reliability has been reported for

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medial and lateral hops for distance (intraclass correlation coefficients, ICC for distance hopped $\geq$0.83), when the hop direction is known in advance (Kea et al., 2001; Vandermeulen et al., 2000). In general, good to excellent reliability for most hip and knee kinematic and kinetic variables has been reported for side-cutting maneuvers, although with low-reliability for kinetics, particularly for knee rotation moment. However, when cutting maneuvers are performed in an unanticipated manner (mimicking sports-specific scenarios), the biomechanical risk factors of ACL injury increase further (Besier et al., 2001a; Brown et al., 2014; Kim et al., 2014; Whyte et al., 2017). So far, to our knowledge no study has investigated the reliability of lower limb kinematics and/or kinetics of unanticipated medial and lateral diagonal hops in individuals with or without knee pathology. Therefore, the aims of this study were to: (1) evaluate the feasibility of a novel one-leg double-hop test consisting of a forward hop followed by a diagonal hop (45°) performed in an unanticipated manner, either medially (UMDH) or laterally (ULDH) upon receiving randomly a visual cue while performing the forward hop; and (2) evaluate the within-session and between-session reliability of 3-dimensional (3D) hip and knee kinematic and kinetic descriptors in UMDH and ULDH for physically active women. It was hypothesized that the test would be feasible and, based on previous reliability studies on side-cutting (Alenezi et al., 2016; Besier et al., 2001b; Marshall et al., 2014; Mok et al., 2017; Sankey et al., 2015), that within-session reliability measures would be higher than between-session reliability measures for all variables.

2. Methods

2.1. Study design and setting

The novel task was successively piloted to determine the distance to hop, angle of cut, and timing and type of the signal given to indicate the direction of hop (medial or lateral). Decisions of task development were based on the difficulty to complete the task, sports-similarity, and the perceived demand on the knee. After finalizing the design, a test-retest reliability study was performed on two occasions within one month (range: 7–30 days). Testing was performed at the U-Motion laboratory, Department of Community Medicine and Rehabilitation, Umeå University, Sweden. The study was approved by the Regional Ethical Review board in Umeå (2015/67–31), and participants' written informed consent

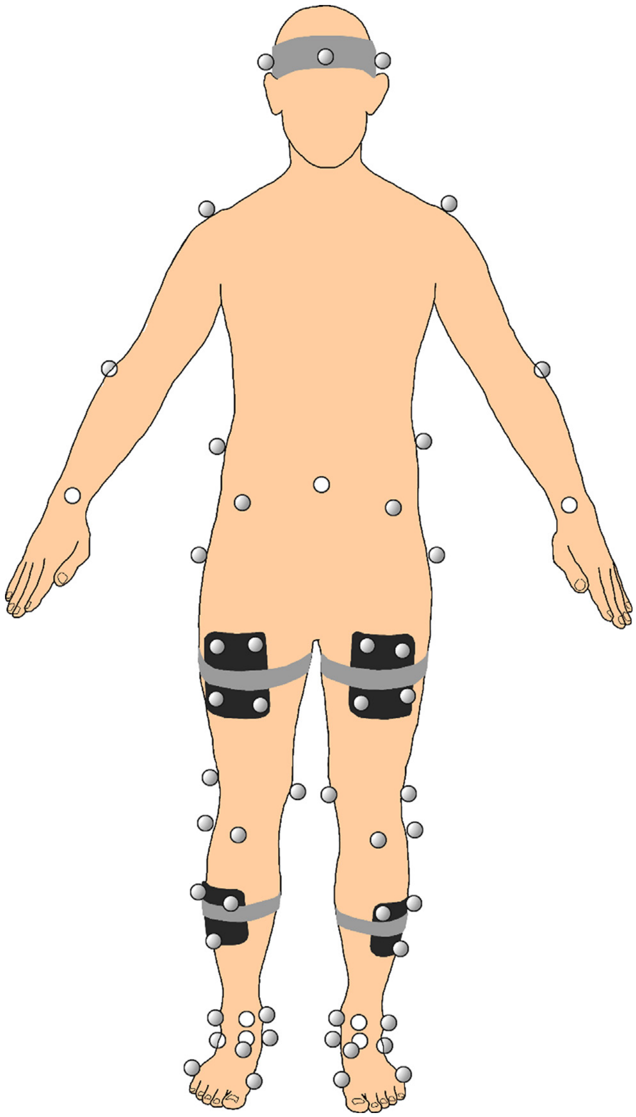

Fig. 1. Marker set configuration. Retroreflective markers were placed on bilateral shoulders, elbows, wrists, iliac crests, anterior superior iliac spines, greater trochanters, lateral and medial femoral epicondyles, tibial tuberosities, the heads of the fibulae, medial and lateral malleoli, sustentaculum tali, lateral calcanei, the proximal and distal ends of the calcanei, the heads of the fifth metatarsals, the first metatarsal heads, and the base of the first metatarsals. In addition, three markers on the head (forehead, right and left), one on the sacrum, a cluster of four markers on a rigid plate for both thighs, and a cluster of three markers on a rigid plate for both shanks were placed.

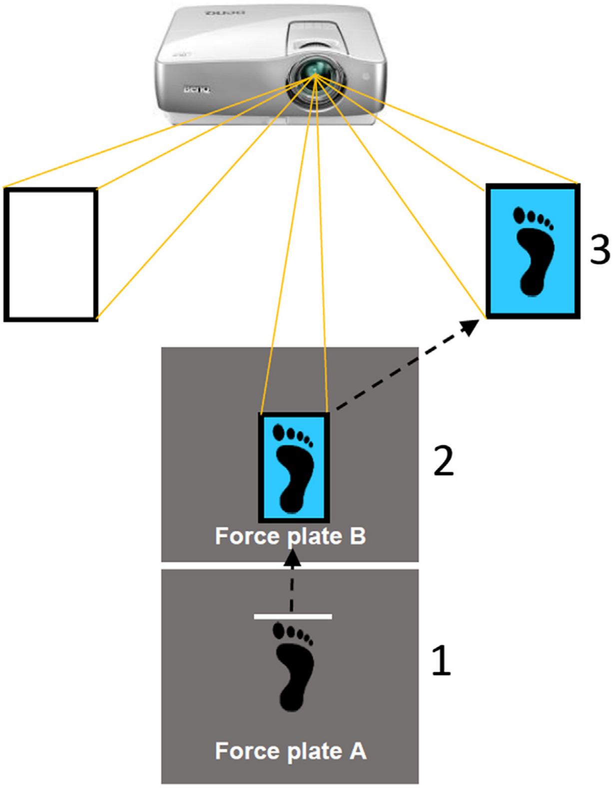

Fig. 2. Schematic representation of an unanticipated lateral diagonal hop (ULDH) of the right lower limb explained in three steps: 1. Starting position with the right foot planted on force plate A; 2. Forward hop landing of the right foot on force plate B at a distance of 25% of their height by reacting to a light signal, illuminated by a ceiling-mounted projector, indicating the landing areas (rectangular boxes) and also the subsequent direction of hopping (randomly ordered); 3. Diagonal hop landing of the right foot in the lateral direction at an estimated angle of 45° and at a distance of 25% of their height.

was obtained. The study complied with the guidelines for reporting reliability and agreement studies (Kottner et al., 2011).

2.2. Participants

For a test-retest design, a minimum of 19 participants was judged sufficient to achieve an ICC of 0.9 (minimal acceptable value: 0.7) with a type I error of 0.05 and type II error of 0.20 (Walter et al., 1998). As there was a risk of unsuccessful attempts for this task of unanticipated nature, we included 22 healthy women (age, 22.3 ± 3.3 years [mean ± SD]; height, 168.6 ± 6.0 cm; body mass, 61.9 ± 7.1 kg; BMI, 21.7 ± 1.8 kg/m^2; median Tegner activity level 6, 2–8 [range]). They did not have any diagnosed musculoskeletal, rheumatic or neurological disorders and were recruited through adverts at the university and by convenience.

2.3. Experimental setup and procedure

An eight-camera 3D motion analysis system (Qualisys, Gothenburg; 240 Hz) and two force plates (Kistler, Winterthur, Switzerland; 1200 Hz) were used. A physiotherapist clinically screened the participants for eligibility.

Prior to testing, relevant demographic and anthropometric data were collected. The leg self-preferred to kick a ball was defined as the dominant leg (right leg for all except one). All participants wore suitable clothing and remained barefoot during the test. The same assessor (JLM) placed 56 retroreflective markers for both test sessions on specific anatomical landmarks (Fig. 1). Participants first performed a standing trial and circumduction movements of the hip to define the hip joint center, and the markers on the femoral epicondyles defined knee joint centers. Thereafter, markers were removed from the sacrum, greater trochanters, medial and lateral femoral epicondyles, and medial malleoli.

2.3.1. Test with unanticipated medial/lateral diagonal hops

Each participant performed two practice trials/leg to familiarize themselves with the task. All unanticipated cutting maneuvers were performed with each leg as quickly as possible after receiving the visual cues indicating the required direction. While hopping with the right leg, cutting done to the left and right sides were named as UMDH and ULDH, respectively. The direction of the unanticipated hop (UMDH/ULDH) was randomly ordered by a computer program with five trials per leg in each direction.

Participants held a 25 cm long rope with both hands behind the back to minimize trunk and arm movements while performing the task. They stood on one leg on force plate A, hopped forward onto force plate B, and then immediately hopped either to the left or to the right at an angle of 45° and landed at a distance of 25% of their height (Fig. 2). The landing target zone was lit up with a light from a ceiling-mounted projector and was illuminated when vertical ground reaction force on force plate A reached below 80% of its peak value during the push-off phase of the forward hop. The time from onset of the light signal (corresponding to the instant referred above) to initial foot contact on force plate B was about 300 ms (±25 ms); this planning time is almost concordant with the minimum threshold (350 ms) used in other studies on unanticipated cutting maneuvers (Borotikar et al., 2008; Kipp et al., 2013).

Table 1
Kinematic and kinetic variables of the deceleration phase of the land-and-cut maneuver associated with unanticipated medial (UMDH) and lateral diagonal hops (ULDH).

Variables	UMDH (n = 21)		ULDH (n = 20)	
	First test mean (95% CI)	Second test mean (95% CI)	First test mean (95% CI)	Second test mean (95% CI)
Peak joint angles (°)				
Hip flexion (+)	45.84 (40.39, 51.29)	46.63 (41.11, 52.15)	44.65 (39.27, 50.04)	45.92 (40.32, 51.52)
Hip abduction (−)	−6.23 (−8.43, −4.04)	−6.97 (−8.82, −5.12)	−2.49 (−4.87, −0.11)	−3.76 (−5.70, −1.81)
Hip adduction (+)	4.05 (1.54, 6.57)	2.56 (0.39, 4.73)	12.87 (9.86, 15.88)	12.30 (9.20, 15.39)
Hip int. rotation (+)	13.88 (10.73, 17.03)	12.96 (9.40, 16.51)	13.62 (10.17, 17.08)	13.65 (9.94, 17.36)
Hip ext. rotation (−)	3.49 (0.50, 6.49)	3.18 (0.05, 6.31)	2.24 (−0.56, 5.04)	2.20 (−0.84, 5.25)
Knee flexion (+)	57.53 (54.41, 60.65)	57.58 (53.25, 61.90)	56.80 (53.36, 60.25)	57.92 (53.45, 62.39)
Knee abduction (−)	−0.03 (−1.90, 1.85)	0.71 (−0.96, 2.39)	2.87 (0.98, 4.77)	2.73 (0.62, 4.85)
Knee adduction (+)	7.95 (5.79, 10.11)	8.88 (6.63, 11.13)	12.03 (9.79, 14.27)	12.05 (9.46, 14.64)
Knee int. rotation (+)	−1.76 (−3.80, 0.28)	−2.66 (−4.77, −0.55)	−2.32 (−4.50,−0.13)	−3.54 (−6.03, −1.04)
Knee ext. rotation (−)	−13.31 (−16.11, −10.52)	−14.37 (−16.90, −11.84)	−15.84 (−18.63, −13.04)	−16.33 (−19.06, −13.61)
Range of motion (°)				
Hip sagittal plane	10.09 (8.40, 11.77)	10.78 (9.23, 12.33)	9.72 (8.82, 10.62)	10.29 (8.70, 11.87)
Hip frontal plane	10.28 (8.68, 11.89)	9.53 (8.35, 10.71)	15.36 (13.22, 17.50)	16.05 (14.04, 18.06)
Hip transverse plane	10.39 (8.51, 12.26)	9.78 (8.14, 11.42)	11.39 (9.29, 13.48)	11.45 (9.16, 13.73)
Knee sagittal plane	41.25 (38.03, 44.48)	40.49 (36.80, 44.18)	41.45 (38.56, 44.34)	41.75 (37.96, 45.54)
Knee frontal plane	7.98 (6.91, 9.05)	8.16 (6.84, 9.49)	9.16 (7.90, 10.42)	9.31 (7.50, 11.13)
Knee transverse plane	11.55 (10.09, 13.01)	11.71 (10.24, 13.19)	13.52 (11.70, 15.35)	12.79 (11.37, 14.22)
Peak joint moments (N.m/kg.m)				
Hip flexion (+)	0.72 (0.62, 0.81)	0.68 (0.59, 0.77)	0.68 (0.59, 0.77)	0.63 (0.57, 0.69)
Hip abduction (−)	0.02 (−0.03, 0.07)	0.01 (−0.05, 0.06)	0.00 (−0.04, 0.05)	−0.01 (−0.05, 0.04)
Hip adduction (+)	0.97 (0.88, 1.05)	1.00 (0.92, 1.09)	1.23 (1.14, 1.33)	1.15 (1.06, 1.25)
Hip int. rotation (+)	0.41 (0.35, 0.48)	0.40 (0.33, 0.48)	0.46 (0.38, 0.55)	0.42 (0.33, 0.51)
Hip ext. rotation (−)	0.03 (0.00, 0.06)	0.02 (0.00, 0.04)	−0.01 (−0.03, 0.01)	−0.01 (−0.04, 0.01)
Knee flexion (+)	1.50 (1.42, 1.59)	1.49 (1.42, 1.57)	1.42 (1.36, 1.49)	1.38 (1.30, 1.47)
Knee abduction (−)	−0.01 (−0.04, 0.02)	0.00 (−0.03, 0.02)	0.00 (−0.03, 0.02)	−0.01 (−0.02, 0.01)
Knee adduction (+)	0.54 (0.46, 0.62)	0.57 (0.49, 0.65)	0.73 (0.64, 0.81)	0.66 (0.58, 0.75)
Knee int. rotation (+)	0.00 (−0.01, 0.01)	−0.01 (−0.02, 0.00)	−0.01 (−0.02, 0.00)	−0.01 (−0.02, −0.01)
Knee ext. rotation (−)	−0.32 (−0.36, −0.28)	−0.34 (−0.39, −0.30)	−0.41 (−0.46, −0.36)	−0.38 (−0.42, −0.34)

CI, confidence interval.
*Mean of test 1 and test 2 scores. †Test 2-Test 1 scores.

Hop success was determined during the tests (JLM) and verified offline (AA). A successful hop required participants to hop in the appropriate direction, achieve the targeted hop distance, and maintain balance for ~3 s upon landing. The hops were unsuccessful if the participants touched the force plate with the non-weight bearing foot, had additional hops or paused upon landing on the force plate, were unable to land within the target zone or released the rope with either hand.

2.4. Kinematic and kinetic analysis

Reflective markers were tracked in Qualisys track manager (QTM-v.2.2, Qualisys AB, Sweden). A full body model consisting of eight rigid segments (trunk, pelvis, thighs, shanks, and feet) and 3D marker coordinates were constructed using Visual 3D (CA Motion Inc., MD, USA). Hip and knee angles were calculated based on the orientation of the distal segment coordinate system in relation to the proximal segment coordinate system, using a Cardan rotation sequence of X (mediolateral axis, flexion[+]-extension[−]), Y (anteroposterior axis, adduction[+]-abduction[−]), Z (longitudinal axis, internal[+]-external rotation[−]). Joint kinetics were derived using the inverse dynamics method and presented as external joint moments. Raw ground reaction force data were used to derive joint moments via inverse dynamic calculations using Visual3D software. Angles and moments were filtered using 15 Hz with a fourth order low-pass Butterworth filter.

Initial contact was defined by an initial increase in vertical ground reaction force of 20 N. Peak ACL strain likely occurs during the initial 40 ms (Koga et al., 2010; Shin et al., 2007) after initial foot contact during cutting/landing, corresponding with the deceleration phase. Therefore, the deceleration phase from initial contact to peak knee flexion (Park et al., 2011) during landing on force plate B was included for analysis.

Investigated variables were range of motion (ROM), peak angles, and peak external moments of the hip and knee in all three planes. A product of body mass and height was used to normalize external joint moments.

2.5. Data analysis and statistics

Three successful trials for each direction (UMDH and ULDH) of one leg/participant (50% dominant and 50% non-dominant) were analyzed considering that the performance of the legs would be expected to be similar in healthy adults (McPherson et al., 2016; Mokhtarzadeh et al., 2017; van der Harst et al., 2007). The Statistical Package for the Social Sciences software (v.23, IBM SPSS statistics, Armonk, New York, USA) was used for analyses with $p < 0.05$ chosen for statistical significance. After testing normality (the Shapiro-Wilk tests), reliability of kinematic and kinetic variables was assessed using ICC for the within- (ICC [3,K], two-way mixed effects, consistency, average/-multiple measurement) and between-session measures (ICC [3,1], two-way mixed effects, consistency, single measurements). As 95% confidence intervals (CI) of ICC are highly recommended to interpret the level of reliability, they are reported in the results (Koo and Li, 2016; Kottner et al., 2011). ICC values were interpreted as poor (<0.50), moderate (0.50–0.74), good (0.75–0.89) or excellent (0.90–1.0) (Koo and Li, 2016). Negative ICC

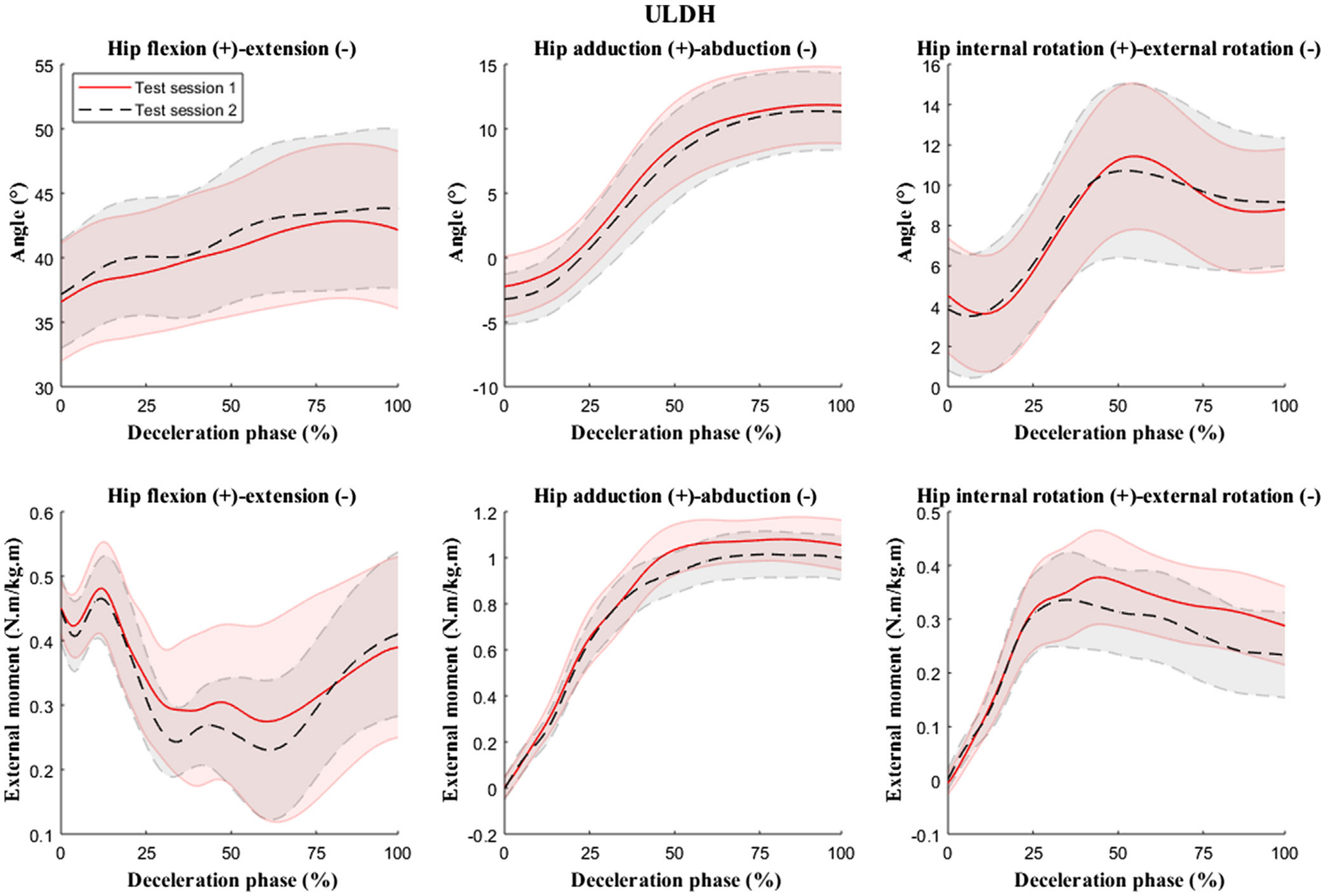

Fig. 3. Ensemble average plots of hip angles and moments (±95% confidence intervals, shaded areas) observed during the deceleration phase of the land-and-cut maneuver of unanticipated lateral diagonal hops (ULDH).

values were set to zero (James et al., 1984). The Koenker tests revealed heteroscedastic errors for certain ROM variables (UMDH: hip frontal plane; ULDH: hip sagittal and transverse planes and knee transverse plane).

Standard error of measurement (SEM) was calculated using $\sigma\sqrt{(1-r)}$ where σ is the standard deviation and r is the reliability coefficient (ICC) (Atkinson and Nevill, 1998; Schuck and Zwingmann, 2003). Moreover, the smallest real difference (SRD) between-session, the threshold for detecting a "real" change beyond measurement error, was defined by $1.96 * \text{SEM} * \sqrt{2}$ (Schuck and Zwingmann, 2003).

Bland-Altman plots and 95% limits of agreement (LoA) were used to depict average scores (d) plotted against the difference between scores to check for outliers, systematic bias, and heteroscedasticity. The LoA was calculated by $d \pm (2 * \text{SD})$ where SD is the standard deviation of difference between the scores, and 95% of the between-session differences are expected to lie within this interval.

3. Results

Nineteen of the 22 participants performed a minimum of three successful trials in both directions while the remaining three had performed only three successful trials in one direction for the analyzed leg (refer Table 1 for number of legs analyzed). Overall, the test was feasible with participants having a hop successful rate of 84 ± 17% (mean ± SD, session 1) and 74 ± 17% (session 2) for UMDH, and 69 ± 22% and 74 ± 18% for ULDH.

3.1. Kinematics and kinetics during UMDH and ULDH

In general, participants exhibited a kinematic and kinetic pattern of hip flexion and internal rotation, and knee flexion, adduction and external rotation for both hop directions. For the first 25% of the deceleration phase, the hip was in adduction for ULDH and abduction (despite adduction moment) for UMDH (Table 1 and Figs. 3–6). Participants moved towards knee internal rotation with time as reflected by decreasing external rotation angles (Figs. 5 and 6); however, the knee internal rotation angles were low (1.76–3.54° of external rotation, Table 1).

3.2. Reliability and agreement of kinematic and kinetic variables of the hip and knee

Within-session reliability was moderate to excellent (ICC CI: 0.67–0.99) and between-session reliability was poor to excellent (ICC CI: 0.22–0.94) for peak angles during UMDH and ULDH. Hip ROM showed poor to moderate reliability (ICC CI: 0–0.71) within- and between-session for both directions. Within-session reliability appeared moderate to excellent (ICC CI: 0.58–0.93) for hip ROM in other planes and poor to excellent (ICC CI: 0.41–0.94) for knee ROM in all three planes. Overall, knee ROM showed poor to good between-session reliability in all three planes for both directions (ICC CI: 0.01–0.80).

Within-session reliability was poor to excellent (ICC CI: 0.23–0.97) for hip moments in all three planes during UMDH and ULDH. Except for knee internal rotation (poor to moderate reliability),

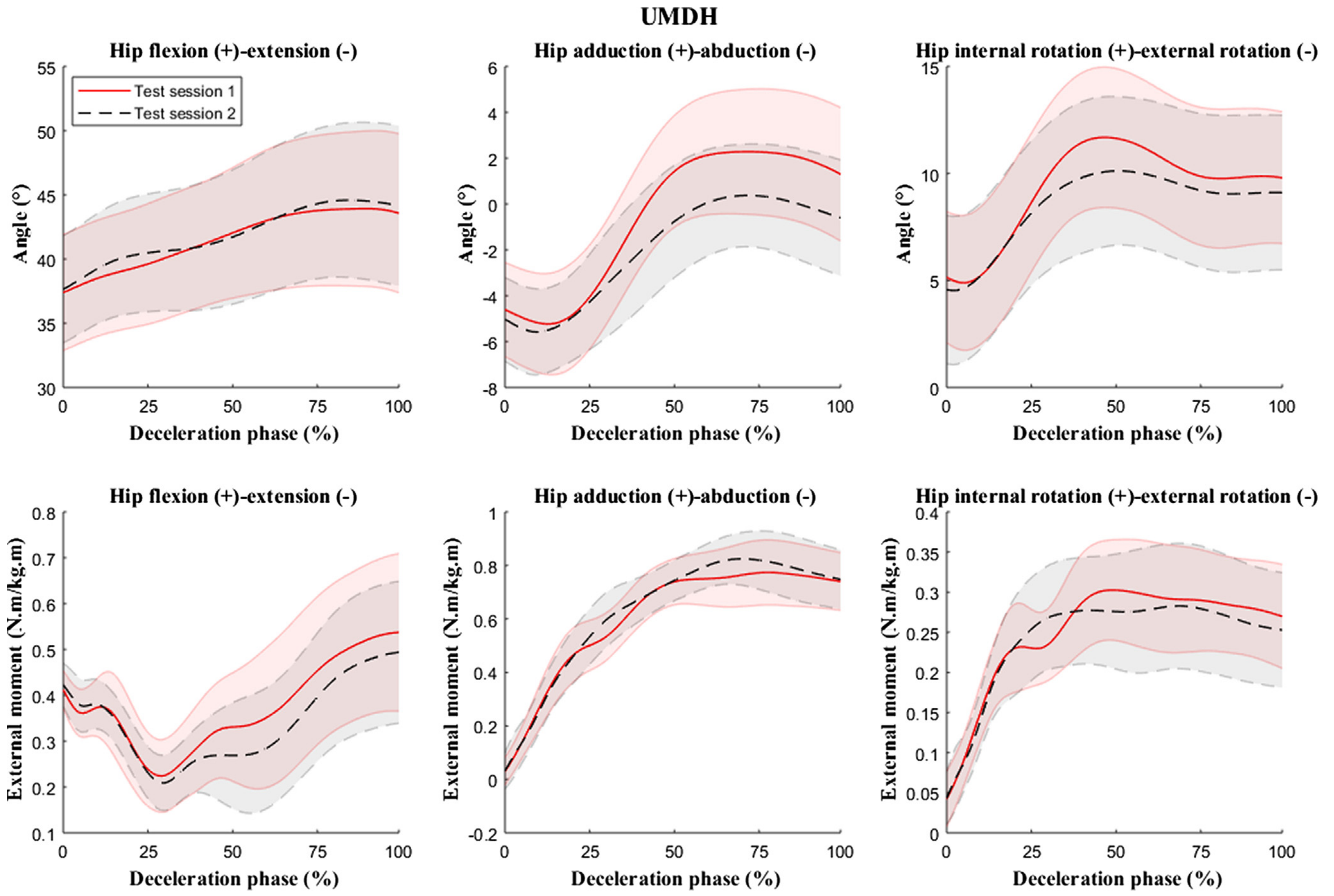

Fig. 4. Ensemble average plots of hip angles and moments (±95% confidence intervals, shaded areas) observed during the deceleration phase of the land-and-cut maneuver of unanticipated medial diagonal hops (UMDH).

within-session reliability of the sagittal and frontal plane knee moments was moderate to excellent (ICC CI: 0.59–0.94) for UMDH but poor to excellent (ICC CI: 0.15–0.94) for ULDH. Between-session reliability was poor to good for all hip and knee moments for both directions (ICC CI: 0–0.86) except for hip internal rotation moment of ULDH that showed moderate to good reliability (ICC CI: 0.58–0.92).

Overall, the SRD values remained lower than their respective means, except for peak angles and/or moments for hip abduction/adduction and external rotation, knee abduction and internal rotation during UMDH and/or ULDH, and hip flexion ROM of UMDH (Tables 1 and 2). Bland-Altman plots for the peak values of key kinematic and kinetic variables are provided as supplementary information (Fig. S1).

4. Discussion

One-leg landing followed by an unanticipated change of direction was considered to increase the difficulty of the novel task by decreasing planning time (≈300 ms). Our novel unanticipated one-leg double-hop test was feasible to perform by healthy females with a mean hop success rate of 69–84%. Owing to the unanticipated nature of the task and given that only five trials per direction were allowed, three of the 22 included participants achieved only three successful trials in one direction for the analyzed leg.

For the hip, similar relative ROM was found for all three planes for UMDH but a greater ROM in both the frontal and transverse planes than the sagittal plane for ULDH. During both UMDH and ULDH, participants had a peak knee flexion ROM ranging from 37 to 46°. A 40% larger knee ROM was observed in the transverse plane compared to the frontal plane for both hop directions. Moreover, the participants performed UMDH and ULDH with the knee adducted and externally rotated during the deceleration phase of the land-and-cut maneuver. Our findings are in agreement with previous studies which reported low knee abduction and internal rotation angles during the loading phase of one-leg drop landing (Nagano et al., 2007; Russell et al., 2006) or land-and-cut maneuvers (Nagano et al., 2009) in females and/or males. Low peak knee abduction and internal rotation angles observed during the deceleration phase of the unanticipated land-and-cut maneuver at 45° (Figs. 5 and 6) imply knee movements that decreases risk for ACL injury (Griffin et al., 2006). Indeed, a cutting angle of 45° places the knee at less risk of an ACL injury than sharper cutting angles (90°, 135° and 180°) (Schreurs et al., 2017). A cutting maneuver performed faster could increase knee loading and vulnerability for ACL injury risk (Fox, 2018) but a diagonal hop (45°) might be slower in speed and differ in trunk and lower limb mechanics compared to a run-and-cut maneuver. In this context, trunk lateral flexion and rotation towards the intended change-of-direction might influence frontal plane knee loads (Fox, 2018). Investigating the influence of trunk motion on lower limb mechanics is beyond the scope of this paper. Even so, we found only low and insignificant correlations (Pearson r = –0.297–0.425; p >0.050) of peak knee adduction moments with corresponding trunk lateral flexion and rotation angles for UMDH/ULDH.

Irrespective of plane, some within-session and nearly all between-session kinetic measures exhibited relatively lesser reliability (ICC: poor/moderate) for both directions when compared to

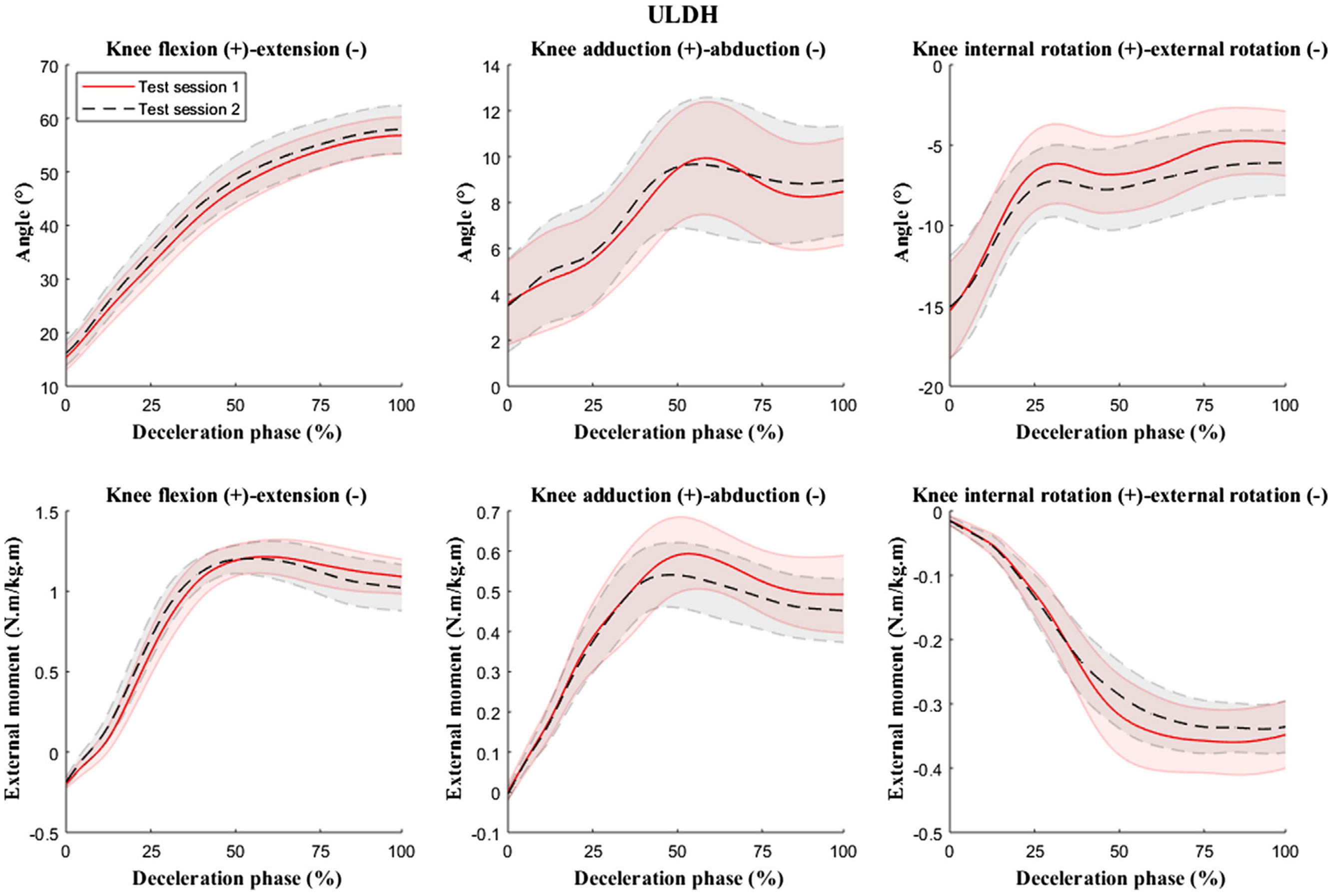

Fig. 5. Ensemble average plots of knee angles and moments (±95% confidence intervals, shaded areas) observed during the deceleration phase of the land-and-cut maneuver of unanticipated lateral diagonal hops (ULDH).

kinematic measures (peak angles, ICC: moderate/excellent). However, the lower limits of 95% CI of ICC were indicating poor reliability for these variables. Reasons for lower ICC can be the variance in data being lower for kinetics between participants and some kinematic and kinetic variables in one or more planes being smaller in magnitude (Table 1, Figs. 3–6). For instance, peak knee flexion angle in UMDH showed a between-session mean difference of 0.05°, SEM 2.80° (5% of mean value), and SRD 7.77° (14% of mean value) with an ICC of 0.66 while peak knee flexion moment had a mean difference of – 0.07 N.m/kg.m, SEM 0.19 N.m/kg.m (13%), and SRD 0.53 N.m/kg.m (36%) with an ICC of 0.34. Variability in kinetics within- and between-session might represent landing strategies, not reflected by kinematics to the same extent, in order to adopt more quickly to changes in the movement demands (McLean et al., 2004) owing to the unanticipated nature of the task.

The means of peak knee abduction and internal rotation angles and/or moments were close to zero during UMDH and/or ULDH which could be attributed to low magnitude and individual-specific variations. The agreement parameters for these variables were smaller than those of other variables because of low ICC and/or σ (cf. SEM formula). On the other hand, they exhibit less agreement when compared to their mean values (means < SEM/SRD). These findings might reflect a strategy adopted by the participants to perform the task in an efficient manner and also mitigate overall risk of injury to the lower limb. During the deceleration phase of landing, the hip adducted and the knee moved towards internal rotation; however, knee external rotation moments were higher in order to control transverse plane movement before cutting towards the correct direction.

The reliability parameters of both UMDH and ULDH are comparable to those of other functional tasks such as side-cut, run, vertical drop jump or drop vertical jump. Our findings are likewise in agreement with Sankey et al. (2015), reporting that kinetic data are more variable than kinematic data during the weight acceptance phase of a side-cutting maneuver, analogous to the deceleration phase of UMDH. Poor to good/excellent between-session reliability of kinematic and kinetic variables of the hip and knee in almost all planes has been demonstrated during side-cutting maneuvers by elite female athletes (n = 41; CI ICC: 0.29–0.90) (Mok et al., 2017), running by recreation athletes of both genders (n = 15; 0.02–0.94) (Alenezi et al., 2016), and walking by healthy adults of both genders (n = 30; −0.19–0.96) (Meldrum et al., 2014). However, poor to moderate between-session reliability has been reported for only peak knee internal rotation moment, while other variables showed moderate to good reliability during the vertical drop jump (Mok et al., 2016). Poor to good/excellent within- and/or between-session reliability of hip adduction and knee internal rotation angles have been observed during 90° side-cuts (n = 15; CI ICC: −0.1–0.87) (Alenezi et al., 2016) and bilateral drop vertical jumps (n = 5; −0.55–0.99) (Earl et al., 2007). Hip abduction/adduction angles (UMDH), hip external rotation, and knee flexion and adduction angles (UMDH and ULDH) exhibited similar between-session reliability estimates in the present study. Sigward and Powers, (2006a, 2006b) reported moderate

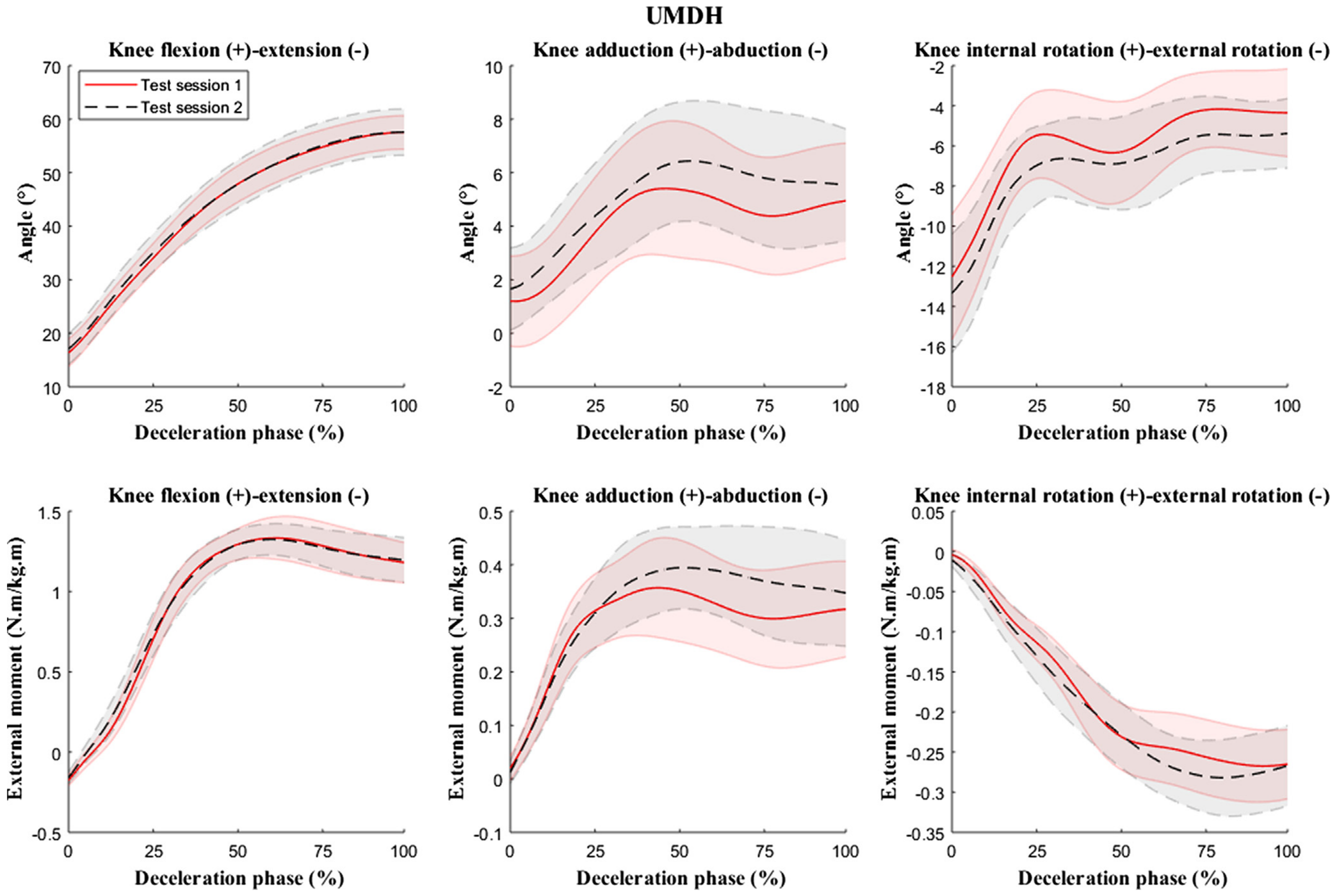

Fig. 6. Ensemble average plots of knee angles and moments (±95% confidence intervals, shaded areas) observed during the deceleration phase of the land-and-cut maneuver of unanticipated medial diagonal hops (UMDH).

Table 2
Reliability (intraclass correlation coefficients [ICC] with confidence intervals [CI]) and agreement (Standard errors of measurement [SEM] and smallest real difference [SRD]) measures for kinematic and kinetic variables of the deceleration phase of landing associated with unanticipated medial (UMDH) and lateral diagonal hops (ULDH).

Variables	UMDH (n = 21)					ULDH (n = 20)				
	Within-session*		Between-session			Within-session*		Between-session		
	ICC (95% CI)	SEM	ICC (95% CI)	SEM	SRD	ICC (95% CI)	SEM	ICC(95% CI)	SEM	SRD
Peak joint angles (°)										
Hip flexion (+)	0.90 (0.79, 0.96)	3.05	0.75 (0.48, 0.89)	3.03	8.39	0.94 (0.86, 0.97)	1.85	0.84 (0.63, 0.93)	1.97	5.47
Hip abduction (−)	0.93 (0.85, 0.97)	0.89	0.59 (0.22, 0.81)	1.86	5.16	0.92 (0.83, 0.97)	1.00	0.78 (0.52, 0.91)	1.11	3.09
Hip adduction (+)	0.91 (0.81–0.96)	1.23	0.63 (0.29, 0.83)	2.01	5.58	0.85 (0.69, 0.94)	2.38	0.80 (0.57, 0.92)	1.30	3.60
Hip int. rotation (+)	0.96 (0.91, 0.98)	0.77	0.80 (0.56, 0.91)	1.54	4.26	0.97 (0.93, 0.99)	0.60	0.83 (0.62, 0.93)	1.29	3.59
Hip ext. rotation (−)	0.97 (0.95, 0.99)	0.42	0.71 (0.42, 0.87)	1.94	5.36	0.96 (0.91, 0.98)	0.66	0.75 (0.47, 0.89)	1.57	4.36
Knee flexion (+)	0.88 (0.76, 0.95)	1.95	0.66 (0.33, 0.85)	2.80	7.77	0.84 (0.67, 0.93)	2.87	0.71 (0.40, 0.88)	2.49	6.91
Knee abduction (−)	0.96 (0.91, 0.98)	0.42	0.84 (0.65, 0.93)	0.67	1.84	0.93 (0.85, 0.97)	0.74	0.86 (0.68, 0.94)	0.61	1.68
Knee adduction (+)	0.93 (0.86, 0.97)	0.80	0.72 (0.43, 0.88)	1.40	3.87	0.91 (0.80, 0.96)	1.13	0.70 (0.39, 0.87)	1.53	4.25
Knee int. rotation (+)	0.96 (0.92, 0.98)	0.46	0.75 (0.49, 0.89)	1.17	3.24	0.96 (0.91, 0.98)	0.49	0.81 (0.59, 0.92)	1.01	2.79
Knee ext. rotation (−)	0.95 (0.89, 0.98)	0.81	0.76 (0.50, 0.90)	1.43	3.97	0.92 (0.84, 0.97)	1.14	0.80 (0.57, 0.92)	1.18	3.27
Range of motion (°)										
Hip sagittal plane	0.35 (0, 0.71)	5.98	0 (0, 0.16)	4.58	12.71	0 (0, 0.49)	5.83	0.14 (0, 0.54)	2.41	6.67
Hip frontal plane	0.82 (0.62, 0.92)	1.57	0.56 (0.18, 0.79)	1.41	3.91	0.82 (0.62, 0.92)	2.07	0.76 (0.50, 0.90)	1.07	2.98
Hip transverse plane	0.83 (0.66, 0.93)	1.70	0.69 (0.37, 0.86)	1.24	3.45	0.80 (0.58, 0.91)	2.25	0.78 (0.52, 0.91)	1.03	2.85
Knee sagittal plane	0.84 (0.68, 0.93)	2.75	0.54 (0.16, 0.79)	3.50	9.68	0.75 (0.48, 0.89)	3.79	0.56 (0.17, 0.80)	3.18	8.82
Knee frontal plane	0.76 (0.51, 0.90)	1.36	0.47 (0.06, 0.75)	1.40	3.89	0.72 (0.41, 0.88)	1.87	0.48 (0.06, 0.76)	1.73	4.80
Knee transverse plane	0.82 (0.63, 0.92)	1.47	0.54 (0.15, 0.78)	1.50	4.15	0.86 (0.71, 0.94)	1.31	0.44 (0.01, 0.74)	1.99	5.51
Peak joint moments (N.m/kg.m)										
Hip flexion (+)	0.92 (0.83, 0.96)	0.05	0.65 (0.31, 0.84)	0.07	0.21	0.81 (0.60, 0.92)	0.09	0.31 (0, 0.66)	0.12	0.32
Hip abduction (−)	0.75 (0.48, 0.89)	0.07	0.22 (0, 0.59)	0.09	0.24	0.77 (0.51, 0.90)	0.06	0.57 (0.18, 0.81)	0.04	0.12
Hip adduction (+)	0.75 (0.49, 0.89)	0.11	0.19 (0, 0.57)	0.15	0.43	0.84 (0.66, 0.93)	0.08	0.68 (0.35, 0.86)	0.07	0.20
Hip int. rotation (+)	0.93 (0.85, 0.97)	0.03	0.67 (0.35, 0.85)	0.05	0.14	0.92 (0.83, 0.97)	0.04	0.81 (0.58, 0.92)	0.04	0.11
Hip ext. rotation (−)	0.86 (0.71, 0.94)	0.02	0.29 (0, 0.64)	0.04	0.11	0.63 (0.23, 0.84)	0.04	0.27 (0, 0.63)	0.04	0.10
Knee flexion (+)	0.80 (0.59, 0.91)	0.09	0.58 (0.21, 0.80)	0.07	0.20	0.60 (0.15, 0.83)	0.14	0.32 (0, 0.66)	0.12	0.32
Knee abduction (−)	0.86 (0.71, 0.94)	0.02	0.33 (0, 0.66)	0.04	0.11	0.60 (0.16, 0.83)	0.05	0.34 (0, 0.67)	0.03	0.07
Knee adduction (+)	0.84 (0.66, 0.93)	0.07	0.38 (0, 0.69)	0.11	0.30	0.85 (0.68, 0.94)	0.07	0.64 (0.29, 0.84)	0.07	0.20
Knee int. rotation (+)	0.36 (0, 0.72)	0.03	0.29 (0, 0.64)	0.12	0.32	0.34 (0, 0.72)	0.03	0.67 (0.33, 0.85)	0.01	0.02
Knee ext. rotation (−)	0.87 (0.72, 0.94)	0.03	0.35 (0, 0.67)	0.06	0.17	0.78 (0.54, 0.91)	0.06	0.57 (0.18, 0.80)	0.04	0.12

Negative ICC values are replaced with zero. Units are not applicable for ICC but valid for SEM and SRD. ICC values less than 0.75 are shown in bold.
Note: The peak values of kinematic and kinetic variables in this Table may not exactly match those observed in the ensemble average plots (Figs. 3–6) because peak values of each variable for all participants may not occur at the same time point during the deceleration phase of the land-and-cut maneuver.
* Reported only for the first test session. CI, confidence interval.

and excellent between-session reliability (n = 5) based on coefficient of multiple correlation for frontal/transverse plane and sagittal knee kinematics, respectively, during side-cutting. Nevertheless, they found excellent reliability for knee moments in all planes (Sigward and Powers, 2006a; Sigward and Powers, 2006b) which is different to our findings for UMDH and ULDH, possibly due to the unanticipated condition. In general, the peak angles had higher ICC than the ROM values of the hip and knee for both directions; this is in disagreement with the findings reported for gait (Meldrum et al., 2014). Nevertheless, the SRD of most kinematic variables (Table 2) was < 5° which is considered as an acceptable threshold for gait measurements (McGinley et al., 2009).

The dynamic and unanticipated nature of the land-and-cut maneuver of UMDH and ULDH might induce variability between trials, sessions, and/or participants depending on one or more factors such as prior anticipation of the hop direction, approach speed of the first hop, stance time, toe-landing, foot rotation, cutting angle, and horizontal forces (showing variation in kinetics without much alteration in kinematics) (Kristianslund et al., 2014; Sankey et al., 2015). Employing more stringent task-execution criteria might influence the aforementioned factors predicting within- and between-session variations in execution of the double-hop task as such. We employed standard criteria for screening of successful hops and selected the first three successful trials with minimal stance time on force plate B for analysis. Though we tried to regulate cutting angle, no strict rules were defined to control the landing (heel-to-toe/toe-to-heel, foot rotation, or approach speed) on force plate B. However, for both directions, $SEM \leq 3°$ (within-session) and $SRD \leq 8.39°$ (between-session) were found for peak angles while peak moments demonstrated $SEM \leq 0.14$ N.m/kg.m and $SRD \leq 0.43$ N.m/kg.m for the hip and knee. These values are slightly different than those of an anticipated 90°-side-cutting task ($SEM \leq 3°/\leq 0.27$N.m/kg and $SRD \leq 14.2°/\leq 1.55$ N.m/kg) (Alenezi et al., 2016), although we expected our unanticipated task to show more variability than anticipated maneuvers. Moreover, a previous study found no effect of using strict task-execution criteria on the reliability of knee kinematics and kinetics observed during side-cutting (Sankey et al., 2015).

Kinematic cross-talk (interpreting one motion as another) was addressed by having the same rater placing the markers and efforts to ensure high accuracy in the procedure of data collection and processing (Piazza and Cavanagh, 2000). We used cluster markers on the thighs to reduce the effects of soft tissue artifacts. The magnitude and change of the position and orientation of the cluster markers are higher during a cutting maneuver compared to walking or one-legged hopping (Benoit et al., 2015). However, the cluster markers have shown comparable performance and better construct validity (less theoretical assumptions throughout the entire model including absence of joint constraints and independence between segments) than the conventional marker set for gait analysis (Collins et al., 2009). Therefore, it is assumed that the cluster markers might be less prone to cross-talk effects from knee flexion especially for frontal plane angles during our task. Artifacts might also arise from using a low cut-off frequency for kinematic data and a high cut-off frequency for kinetic data (Kristianslund et al., 2012). However, the same cut-off frequency (15 Hz) was used to filter angles and moments to remove random artifacts and prevent over-smoothing of the data.

Only healthy women were investigated which precludes generalizing the results to healthy men or adults with knee disorders. However, we have included women with Tegner scores 2–8 in order to reflect a continuum of physical activity levels (light activities to competitive sports). Such a continuum might provide a wide range of scores in the variables of interest, which is desirable when investigating reliability.

Laboratory-based unanticipated double-hop tests, partially mimicking cutting maneuvers, cannot exactly replicate actual game scenarios but might be helpful in challenging dynamic knee control in one or more planes. An anticipated land-and-cut maneuver might demonstrate altered lower limb mechanics compared to its unanticipated counterpart (Almonroeder et al., 2015) and whether reliability estimates differ between them needs investigation. Our participants did not perform anticipated trials; however, future studies are warranted that investigate reliability of trunk and lower limb mechanics of anticipated and unanticipated hopping maneuvers while also comparing individuals with and without ACL injuries of both genders.

In summary, the novel one-leg double-hop test was feasible to perform by healthy women. Within-session peak hip and knee angles and moments were more reliable than between-session measurements for UMDH and/or ULDH. Low peak knee abduction and internal rotation angles/moments observed during this task indicate less vulnerability of the knee to ACL injury risk. However, the relatively large ROM in the frontal and transverse planes (ULDH > UMDH) might challenge dynamic knee control, and therefore the novel task might be useful for evaluating knee function during rehabilitation of ACL injuries.

Conflict of interest statement

None.

Ethical approval

The Regional Ethical Review board in Umeå approved the study (reference: 2015/67-31).

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2018.10.015.

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