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Altered biomechanical strategies and medio-lateral control of the knee represent incomplete recovery of individuals with injury during single leg hop

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ABSTRACT

Anterior cruciate ligament (ACL) injury can result in failure to return to pre-injury activity levels and future osteoarthritis predisposition. Single leg hop is used in late rehabilitation to evaluate recovery and inform treatment but biomechanical understanding of this activity is insufficient.

This study investigated single leg hop for distance aiming to evaluate if ACL patients had recovered: (1) landing strategies and (2) medio-lateral knee control. We hypothesized that patients with reconstructive surgery (ACLR) would have more similar landing strategies and knee control to healthy controls than patients treated conservatively (ACLD).

16 ACLD and 23 ACLR subjects were compared to 20 healthy controls (CONT). Kinematic and ground reaction force data were collected while subjects hopped their maximum distance. The main output parameters were hop distance, peak knee flexor angles and extensor moments and *Fluency* (a measure introduced to represent medio-lateral knee control). Statistical differences between ACL and control groups were analyzed using a general linear model univariate analysis, with COM velocity prior to landing as covariate.

Hop distance was the smallest for ACLD and largest for CONT ($p<0.001$; ACLD 57.1 ± 14.1; ACLR 75.1 ± 17.8; CONT 77.7 ± 14.07% height). ACLR used a similar kinematic strategy to CONT, but had a reduced peak knee extensor moment ($p<0.001$; ACLD 0.32 ± 0.14; ACLR 0.31 ± 0.16; CONT 0.42 ± 0.13 BW.height). *Fluency* was reduced in both ACLD and ACLR ($p=0.006$; ACLD 0.13 ± 0.34; ACLR 0.14 ± 0.34; CONT 0.17 ± 0.41 s).

Clinical practice uses hopping distance to evaluate ACL patients' recovery. This study demonstrated that aspects such as movement strategies and knee control need to be evaluated.

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1. Introduction

Two major impacts of ACL rupture, whether treated conservatively or surgically, are failure to return to pre-injury activity levels (Myklebust et al., 2003; Gobbi and Francisco, 2006; Strehl and Eggli, 2007; Ardern et al., 2011a) and future predisposition to osteoarthritis (Blagojevic et al., 2010). A review evaluating return to sport following ACL injury indicated that up to 48% was not returning to their pre-injury sporting levels (Ardern et al., 2011a).

Medio-lateral knee control is an important factor to assess in ACL injured patients. Besides adductor moments, clinical evidence suggests that fluency of movement is an aspect of medio-lateral knee control that is worth investigating. This study therefore investigated recovery of both these aspects of knee control in ACL patients. Regardless of whether injury is managed conservatively or surgically, rehabilitation is recommended to maximize recovery and performance. Current rehabilitation methods recommend strengthening, neuromuscular control, perturbation and plyometric exercise (Risberg et al., 2009; Eitzen et al., 2010; Hartigan et al., 2010; Escamilla et al., 2012; Wilk et al., 2012) but evidence is inconclusive on the biomechanical effect and clinical effectiveness of individual exercises (Escamilla et al., 2012; Button et al., 2012).

Single leg hop is an exercise used in late stage rehabilitation and a tool to evaluate recovery and inform treatment selection (Ardern et al., 2011b; Grindem et al., 2011). This activity challenges

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knee stability by requiring large knee moments during take-off and landing and mimics some maneuvers encountered on return to sport. Clinically the symmetry index of the injured and non-injured hop distance is frequently used to evaluate hop performance (Engelen-van Melick et al., 2012; Grindem et al., 2011). However, reduced performance of the non-injured leg can exaggerate estimation of recovery (Button et al., 2005).

There is no consensus in the literature on the recovery of hop distance for ACLR individuals (Gokeler et al., 2010; Orishimo et al., 2010). ACLD individuals on the other hand have been reported not to recover hop distance (Gauffin et al., 1990; Scavenius et al., 1999; Button et al., 2006; Gustavsson et al., 2006). Only a limited number of previous studies have analyzed 3D kinematic and kinetic hop performance of ACL injured individuals. Differences in hop performance have been reported between high and poor functioning ACLD individuals (Rudolph et al., 2000); with high functioning ACLD having unchanged knee kinematics and an increased contribution of the ankle to the total support moment, and poor functioning ACLD using a smaller range of knee flexion, a lower peak vertical ground reaction force, lower knee extensor moments and greater contribution from the hip to the total support moment. Compared to healthy controls, ACLD individuals performed a single leg hop for distance using higher moments at the ankle and hip, more forward trunk lean and a more anterior ground reaction force vector (Oberländer et al., 2012). ACLR individuals demonstrated a reduced knee range of motion during the landing phase in some (Orishimo et al., 2010 and Deneweth et al., 2010) but not all studies (Gokeler et al., 2010).

Besides these kinematic and kinetic differences reported on single leg hopping in ACL injured individuals, there are no studies investigating how this movement challenges motor control. Recovery of motor control is essential for return to sports and therefore an important aspect of rehabilitation. This study therefore investigated the movement strategies used during the landing phase of a single leg hop for distance. This landing phase consists of a phase where the forward velocity of the center of mass (COM) is decelerated. COM deceleration can be achieved by a telescopic strategy where the stance leg shortens. This strategy requires high knee extensor moments and puts high demands on dynamic knee control. COM deceleration can also be achieved by using a pendular strategy where COM rotation around the ankle is controlled. This strategy requires smaller knee extensor moments and requires less medio-lateral knee control, but larger hip flexion and plantar flexion moments. A Telescopic Inverted Pendulum (TIP) analysis (Jacobs and van Ingen Schenau, 1992; Papa and Cappozzo 1999; van Deursen and Phillips, 2006) can be used to identify if the landing phase is predominantly telescopic or pendular.

Clearly a better understanding of knee control during functional movements is needed to be able to improve rehabilitation outcome. This study therefore investigated a single leg hop for distance, which challenges knee stability, with the aims of evaluating if:

1) Landing strategies in ACLD and ACLR have been recovered to those of healthy control subjects and
2) medio-lateral control has been recovered in ACLD and ACLR.

We hypothesized that ACL injury would result in altered landing strategies and reduced medio-lateral knee control compared to healthy controls. In addition, we hypothesized that ACLD patients would be more affected in their landing strategies and medio-lateral knee control compared to ACLR.

2. Methods

21 ACLD, 23 ACLR and 20 healthy control (CONT) subjects provided informed consent to participate in this study (subject demographics are in Table 1). ACL subjects were recruited from a typical clinical (non-elite sporting) population. All ACLR had a four strand gracilis-semitendinosus tendon graft reconstruction. Ethical approval for this study was obtained from the South East Wales Research Ethics Committee. Inclusion criteria were that patients were aged between 18 and 65 years, had an ACL rupture (ACLD group), or a primary ACL reconstruction (ACLR group) that may or may not be accompanied with a meniscal tear, collateral ligament sprain, or cartilage and sub-cortical bone bruises; had finished their rehabilitation; had no other pathology which affects their movement; had no previous knee surgery and were able to provide informed consent independently. The typical population of patients seen in the hospital setting are not elite athletes and the distribution of injuries is mixed. For this study ACL injury is the dominant feature. All of our subjects had MRI scans taken and those were assessed by an expert clinician to decide whether they fit into the category of a typical injury. Our approach has been to filter out individuals who had locked knees, fractures, MCL, PCL and posterior lateral corner complete ruptures. However, when we explored the number of subjects that have a singular ACL injury, our finding was that this hardly ever occurs without at least some comorbidity. Therefore, a representative sample of ACL injured individuals has to include people with MCL sprains, meniscal tears, as well as cartilage and sub-cortical bone bruises. The ACLD did not have surgery because they were either copers (as in they were functioning extremely well), adapters (as in they were willing to adjust their activity level), non-copers waiting for surgery, or a decision about surgery had not yet been made.

Knee function was scored for ACLD and ACLR using the International Knee Documentation Subjective Knee (IKDC) questionnaire (Irrgang et al., 2001). Knee extensor ($S_{KneeExt}$) and flexor ($S_{KneeFlex}$), and hip abductor (S_{HipAbd}) and adductor (S_{HipAdd}) isokinetic strength were measured at 90 °/s and 45 °/s respectively on a Biodex System 4 PRO dynamometer (Biodex Medical Systems Inc, USA). This was measured on both legs, but presented for the injured (ACLR and ACLD) and the dominant stance leg (CONT) only.

Individuals were asked to hop their maximum single leg hop distance and regain their balance after landing. The hop distance was marked from the force platform and subjects were then asked to perform four single leg hops for maximum distance from this mark, as such that they would land on the force platform. All ACL injured subjects hopped using their injured leg and the controls using their dominant stance leg. This was based on findings from a previous study that hopping in healthy subjects was virtually identical (within about 5%) for the dominant and non-dominant leg (Figure 6, Button et al., 2005). Furthermore, in knee injured subjects the non-injured leg was affected and therefore cannot be used for comparison.

For each subject hopping trials were collected until at least four successful hopping trials were achieved where they landed on the force platform and were able to regain balance without touching the floor with the other foot. Prior to this a static anatomical calibration trial was collected. Kinematic data were collected at 250 Hz using an eight camera VICON MX motion analysis system (Oxford Metrics Group Ltd., UK). Reflective markers were placed using the 'Plug-in-Gait' full body marker set. The knee axes were aligned using the anatomical calibration trial. Two additional markers were placed on the left and right lateral sides of the iliac crest (LILC and RILC). Ground reaction force data were collected using a Kistler force plate (Kistler Instruments Ltd., Switzerland) at 1000 Hz. In some trials the trunk flexed as such that the markers on the left and right anterior superior iliac crests (LASI and RASI) were occluded; these gaps were filled using a custom written program in Vicon BodyBuilder for Biomechanics (version 1.2, Oxford Metrics Group Ltd., UK) and the data of the LILC and RILC markers.

Inverse dynamics calculations were performed within VICON Nexus software (version 1.6.1) and data were further processed and analyzed in Matlab R2010b (The Mathworks Inc., USA). This analysis focused on the landing phase of the single leg

Table 1
Demographics of ACL deficient (ACLD), ACL reconstructed (ACLR) and healthy control (CONT) subjects, with mean and standard deviations. A* indicates significant difference from CONT ($p < 0.025$).

	Gender (M=male, F=female)	Age (years)	Height (m)	Mass (kg)	IKDC score	$S_{KneeExt}$ (BW.height)	$S_{KneeFlex}$ (BW.height)
ACLD	F: 3; M: 18	32 ± 8	1.77 ± 0.08	80.6 ± 15.0	65 ± 12*	0.10 ± 0.02	0.06 ± 0.02*
ACLR	F: 4; M: 19	28 ± 9	1.74 ± 0.06	79.0 ± 10.1	86 ± 9	0.10 ± 0.03	0.06 ± 0.02*
CONT	F: 9; M: 11	29 ± 8	1.74 ± 0.11	74.8 ± 16.5	–	0.11 ± 0.03	0.07 ± 0.02

hop for distance. Anthropometric measurements were recorded (height, weight, leg length, knee width and ankle width) and used for the inverse dynamic calculations.

Hop performance was quantified as this could influence landing strategies and knee control. Parameters used for hop performance were hopping distance (d_{hop}), COM velocity along the axis of hopping movement prior to landing (v_{COM}) and duration of the COM deceleration phase during landing (t_{dec}). d_{hop} was calculated as the distance the ankle joint center traveled along the axis of hopping. d_{hop} was normalized to body height. To investigate the kinematics and kinetics, a telescopic inverted pendulum (TIP) model approach was used (Fig. 1; Jacobs and van Ingen Schenau, 1992; Papa and Cappozzo, 1999; van Deursen and Phillips, 2006). Hopping can be simulated by an inverted pendulum model where the stance limb is modeled as a rigid segment between the ankle and COM that rotates around the ankle. The TIP model approach will show whether ACL injured individuals use a predominantly telescopic motion (large change in the distance between the ankle and COM (L_{COM})) or predominately pendular motion (large change of the approach angle of the COM (θ_{COM})). Further output variables for the TIP analysis were calculated in Matlab using the kinematic and kinetic data. These variables were knee flexion–extension range of motion (ROM_{knee}), peak internal knee extensor moment ($M_{knee(max)}$), knee flexion angle at $M_{knee(max)}$ ($\theta_{knee(Mknee(max))}$), peak hip moment ($M_{hip(max)}$), peak ankle moment ($M_{ankle(max)}$), and trunk lean at the peak knee extensor moment, calculated as the sagittal plane angle of line connecting pelvis and shoulder markers' average ($\theta_{trunkAP}$).

The landing phase of the single leg hop was also analyzed in the coronal plane to investigate medio-lateral control of the knee joint with the following output variables: the peak external adductor moment ($M_{add(max)}$), which was normalized using body weight (BW) and height, the maximum medio-lateral distance between the projection of the ankle and knee on the ground (D_{knee}), and trunk lean ($\theta_{trunkML}$, calculated as $\theta_{trunkAP}$ but in the coronal plane). The peak external and not internal adductor moment was calculated, as this term is most commonly used in literature. Fluency of the knee movement in the coronal plane was calculated by a method adapted from Smeulders et al. (2001). It was defined as the number of times the velocity of the knee position in the coronal plane crossed zero, averaged per second. The inverse of this measure (Period (s): $T=1/f$) was used so that a larger value agreed with a more fluent movement.

After checking for normal distribution, statistical differences for the output variables between the ACL and control groups were analyzed using a general linear model univariate analysis. COM velocity prior to landing (v_{COM}) was used as a covariate. An alpha level of $p<0.05$ was used to evaluate statistically significant between-groups difference. When between-group differences were significant, a polynomial first order (linear) contrast post hoc test was performed to evaluate if either ACLD < ACLR < CONT or ACLD > ACLR > CONT (alpha level of $p<0.05$). If there was no significant linear contrast a secondary post hoc analysis using a simple contrast was performed to evaluate differences in ACLD and ACLR from CONT (alpha level of $p<0.025$). Pearson's correlations were used to explore the relation between output variables and subject characteristics.

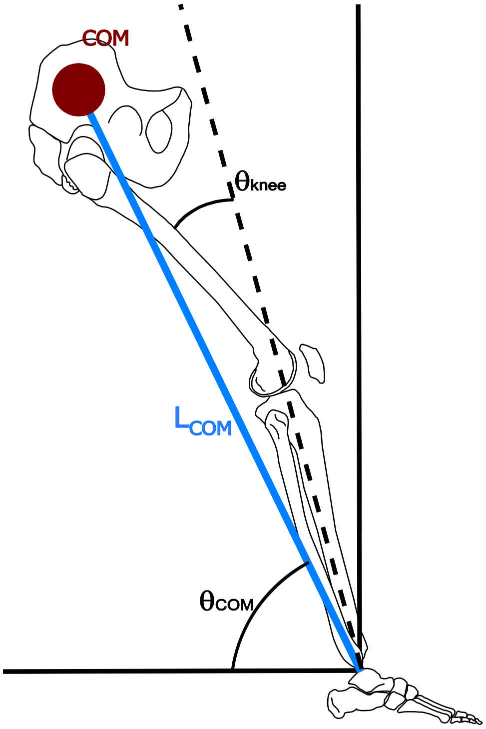

Fig. 1. Schematic overview TIP model, with the COM angle (θ_{COM}), knee angle (θ_{knee}), and distance ankle to COM (L_{COM}).

3. Results

The subject groups were reasonably matched for age, height and mass (Table 1). There was however a larger proportion of female subjects in the CONT group (CONT: 9 females and 11 males; ACLR: 4 females and 19 males; ACLD: 3 females and 18 males; Table 1). ACLD scored on average lower in the IKDC questionnaire than ACLR (ACLD: 65 ± 12; ACLD: 86 ± 9; Table 1), which means that they had lower knee function. The time since injury had a range of 3–240 months in ACLD and 10–83 months in ACLR. There were two ACLD subjects who were 132 and 240 months post injury, otherwise ACLD ranged between 3 and 34 months post injury. Visual inspection of the main output variables demonstrated that these subjects were not outliers and could be included in this study. Time since surgery in ACLR ranged between 7 and 36 months. Relevant correlations between output variables and subject characteristics were not found significant (e.g. d_{hop}/time since injury: $r=231$; $p=0.132$ in ACLD). Relative knee extensor ($S_{KneeExt}$) strength was not significantly different between groups, while relative knee flexor ($S_{KneeFlex}$) strength was significantly reduced in ACLR and ACLD compared to CONT (CONT: $S_{KneeExt}$: 0.11 ± 0.03, $S_{KneeFlex}$: 0.07 ± 0.02; ACLR: $S_{KneeExt}$: 0.10 ± 0.03, $S_{KneeFlex}$: 0.06 ± 0.02; ACLD: $S_{KneeExt}$: 0.10 ± 0.02, $S_{KneeFlex}$: 0.06 ± 0.02; Table 1).

All ACLR and CONT subjects were able to hop, while five ACLD subjects were unable to. There was a significant between group difference in hop distance (d_{hop}) ($p<0.001$) and a significant linear contrast (CONT: 77.7 ± 14.1; ACLR: 75.1 ± 17.8; ACLD: 57.1 ± 14.1% height; $p<0.001$; Table 2). The COM velocity prior to landing (v_{COM}) was significantly different between groups ($p<0.001$) and had a significant linear contrast (CONT: 1.74 ± 0.38; ACLR: 1.71 ± 0.40; ACLD: 1.28 ± 0.34 m/s; $p<0.001$; Table 2). V_{COM} was taken as a covariate in further statistical analysis to take account of the difference in hop performance. The time taken to decelerate the COM after landing (t_{dec}) was not significantly different between the groups when v_{COM} was taken into account (CONT: 0.052 ± 0.016; ACLR: 0.058 ± 0.020; ACLD: 0.050 ± 0.018 s; $p=0.064$; Table 2).

TIP model analysis (Fig. 1) was used to evaluate group differences in movement strategies. Fig. 2 shows that the kinematic strategy used by ACLR is similar to that used by CONT, while ACLD used a different strategy. ACLD landed with a more upright posture (θ_{COM} closer to 90°) than ACLR and CONT, and had a smaller change in L_{COM} during the landing phase. This was further confirmed by a significant group difference in knee flexion/extension range of motion throughout landing (ROM_{knee}) ($p=0.018$); there was a significant linear contrast in ROM_{knee} with the smallest range of motion in ACLD and the largest in CONT (CONT: 69.0 ± 15.7; ACLR: 63.7 ± 13.3; ACLD: 59.1 ± 15.6°; $p=0.009$; Table 3).

Table 2
Hop performance of ACLD, ACLR and CONT subjects, with mean and standard deviations. d_{hop} is the hop distance, v_{COM} is the COM velocity prior to landing and t_{dec} is the time taken to decelerate. A $^{\&}$ indicates a significant linear contrast between the subject groups ($p<0.05$). A * indicates a significant difference between ACLD or ACLR and CONT ($p<0.025$).

	HOP PERFORMANCE			
	Hop ability	**d_{hop} (% height)$^{\&}$**	**v_{COM} (m/s)$^{\&}$**	**t_{dec} (s)**
ACLD	Yes: 16; no: 5	57.1 ± 14.1	1.28 ± 0.34	0.050 ± 0.018
ACLR	Yes: 23; no: 0	75.1 ± 17.8	1.71 ± 0.40	0.058 ± 0.020
CONT	Yes: 20, no: 0	77.7 ± 14.1	1.74 ± 0.38	0.052 ± 0.016

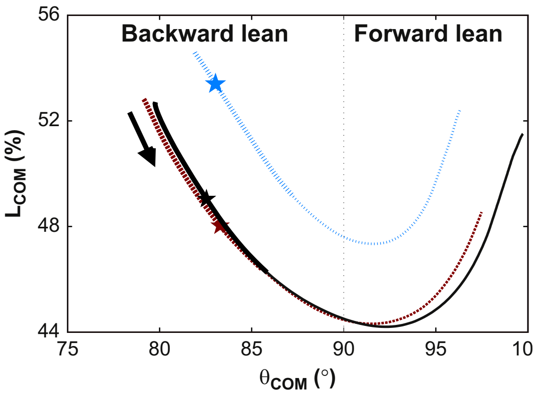

Fig. 2. TIP model analysis with distance ankle to COM as percentage body height (L_{COM}) against angle of COM (θ_{COM}). The black solid line is the average for CONT; the red coarsely dashed line the average for ACLR; and the blue finely dashed line the average for ACLD. Stars are the peak knee extensor moments. And the thick parts of the lines indicate the deceleration phase of the hop. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
TIP analysis of ACLD, ACLR and CONT subjects, with mean and standard deviations. $\theta_{knee(Mknee(max))}$ is the COM angle at the peak knee extensor moment, ROM_{knee} is the knee flexion/extension range of motion throughout landing, $M_{knee(max)}$ is the peak knee extensor moment, $\theta_{knee(Mknee(max))}$ is the knee flexion angle at peak knee moment, $M_{hip(max)}$ is the peak hop moment, $M_{ankle(max)}$ is the peak ankle moment, $\theta_{trunkAP}$ is the forward lean of the trunk at the peak knee extensor moment, and $\theta_{COM(Mknee(max))}$ is the COM angle at the peak knee extensor moment. A & indicates a significant linear contrast between the subject groups ($p<0.05$). A * indicates a significant difference between ACLD or ACLR and CONT ($p<0.025$).

	TIP ANALYSIS		
	ACLD	ACLR	CONT
ROM_{knee} (°)$^{\&}$	59.1 ± 15.6	63.7 ± 13.3	69.0 ± 15.7
$M_{knee(max)}$ (BW.height)	0.32 ± 0.14	$0.31 \pm 0.16^{*}$	0.42 ± 0.13
$\theta_{COM(Mknee(max))}$ (°)	86.9 ± 4.1	83.5 ± 5.1	81.9 ± 4.3
$M_{hip(max)}$ (BW.height)$^{\&}$	0.56 ± 0.24	0.60 ± 0.19	0.50 ± 0.18
$M_{ankle(max)}$ (BW.height)$^{\&}$	0.36 ± 0.10	0.31 ± 0.10	0.29 ± 0.10
$\theta_{knee(Mknee(max))}$ (°)	36.2 ± 10.2	36.3 ± 10.7	38.8 ± 8.3
$\theta_{trunkAP}$ (°)	10.2 ± 6.6	12.2 ± 7.0	12.7 ± 7.2

There was a significant group difference in peak internal knee extensor moment ($M_{knee(max)}$) ($p<0.001$) but there was no significant linear contrast ($p=0.056$). Secondary post hoc analysis demonstrated ACLR had a significantly reduced $M_{knee(max)}$ compared to CONT ($p<0.001$) but there was no significant difference in $M_{knee(max)}$ between ACLD and CONT (CONT: 0.42 ± 0.13; ACLR: 0.31 ± 0.16; ACLD: 0.32 ± 0.14 BW.height; $p=0.056$; Table 3). The peak hip flexion moment ($M_{hip(max)}$) was significantly different between groups ($p<0.001$); there was a significant linear contrast (CONT: 0.50 ± 0.18; ACLR: 0.60 ± 0.19; ACLD: 0.56 ± 0.24 BW.height; $p<0.001$; Table 3). Plantar flexion moment ($M_{ankle(max)}$) was significantly different between groups ($p<0.001$); again the linear contrast was significant (CONT: 0.29 ± 0.10; ACLR: 0.31 ± 0.10; ACLD: 0.36 ± 0.10 BW.height; $p<0.001$; Table 3).

Key features of posture at $M_{knee(max)}$ were comparable in ACLD, ACLR and CONT; there were no significant group differences in knee flexion angle at peak knee moment ($\theta_{knee(Mknee(max))}$) (CONT: 38.8 ± 8.3; ACLR: 36.3 ± 10.7; ACLD: 36.2 ± 10.2°; $p=0.207$; Table 3); and there was no significant difference in the forward lean of the trunk ($\theta_{trunkAP}$) at peak knee moment (CONT: 12.7 ± 7.2; ACLR: 12.2 ± 7.0; ACLD: 10.2 ± 6.6°; $p=0.449$; Table 3); also the COM angle at $M_{knee(max)}$ ($\theta_{COM(Mknee(max))}$) was not significantly different between groups (CONT: 81.9 ± 4.3; ACLR: 83.5 ± 5.1; ACLD: 86.9 ± 4.1°; $p=0.056$; Table 3).

Table 4
Medio-lateral control output parameters of ACLD, ACLR and CONT subjects, with mean and standard deviations. $D_{knee(max)}$ is the maximum medio-lateral displacement of the knee relative to the ankle, $D_{knee(Mknee(max))}$ is the medio-lateral displacement of the knee relative to the ankle at the peak knee moment, $M_{add(max)}$ is the peak knee adduction moment, $\theta_{trunkML}$ is the medio-lateral trunk lean at peak knee moment. A & indicates a significant linear contrast between the subject groups ($p<0.05$). A * indicates a significant difference between ACLD or ACLR and CONT ($p<0.025$).

	MEDIO-LATERAL CONTROL		
	ACLD	ACLR	CONT
Fluency (s)$^{\&}$	0.13 ± 0.34	0.14 ± 0.34	0.17 ± 0.41
$D_{knee(max)}$ (m)$^{\&}$	0.040 ± 0.033	0.023 ± 0.038	0.006 ± 0.039
$D_{knee(Mknee(max))}$ (m)	0.028 ± 0.016	0.028 ± 0.018	0.030 ± 0.017
$M_{add(max)}$ (BW.height)$^{\&}$	0.32 ± 0.02	$0.33 \pm 0.01^{*}$	0.30 ± 0.01
$\theta_{trunkML}$ (°)	8.9 ± 3.4	$9.1 \pm 4.1^{*}$	10.8 ± 4.3

Fluency of the knee movement in the coronal plane was significantly different between groups ($p=0.006$) and demonstrated a significant linear contrast (CONT: 0.17 ± 0.41; ACLR: 0.14 ± 0.34; ACLD: 0.13 ± 0.34 s; $p=0.006$; Table 4). This means knee movement was least fluent in ACLD and most fluent in CONT. The maximum medio-lateral displacement of the knee relative to the ankle ($D_{knee(max)}$) showed significant group differences ($p=0.009$) with a significant linear contrast (CONT: 0.006 ± 0.0039; ACLR: 0.023 ± 0.038; ACLD: 0.040 ± 0.033 m; $p<0.003$; Table 4). This means ACLD moved their knee most medial relative to the ankle. At peak knee moment there was however no group difference in medial displacement ($D_{knee(Mknee(max))}$) (CONT: 0.030 ± 0.017; ACLR: 0.028 ± 0.018; ACLD: 0.028 ± 0.016 m; $p=0.641$; Table 4). Peak knee adduction moments ($M_{add(max)}$) were significantly different between groups ($p<0.05$) and there was a significant linear contrast with the highest $M_{add(max)}$ in ACLR and the lowest in CONT (CONT: 0.30 ± 0.01; ACLR: 0.33 ± 0.01; ACLD: 0.32 ± 0.02 BW.height; $p=0.01$; Table 4). There was a significant group difference for medio-lateral trunk lean at peak knee moment ($\theta_{trunkML}$) ($p=0.025$) but no linear contrast ($p<0.628$; Table 4). Secondary post hoc analysis identified that ACLR use significantly less $\theta_{trunkML}$ than CONT ($p=0.009$) but there was no difference between ACLD and CONT (CONT: 10.8 ± 4.3; ACLR: 9.1 ± 4.1°; ACLD: 8.9 ± 3.4°; $p=0.628$; Table 4). The difference in $\theta_{trunkML}$ between ACLR and CONT was however only 1.7° and therefore not considered meaningful.

4. Discussion

This study investigated recovery of landing strategies and medio-lateral knee control during a single leg hop for distance in ACLD and ACLR individuals.

All CONT and ACLR subjects were able to hop whereas some ACLD were unable to. The ACLD that were able to hop did not perform as well as the other groups with a reduced hop distance (d_{hop}) and COM velocity prior to landing (v_{com}). Despite the decreased d_{hop} and v_{com} ACLD required the same amount of time to decelerate (t_{dec}) in the landing phase as CONT. ACLD had the greatest reduction in hop performance compared to CONT. ACLR performed at an intermediate level between ACLD and CONT. Consequently a pattern of ACLD < ACLR < CONT does emerge for hop performance, which was consistent with our expectations. The reduced hop distance in ACLD and ACLR could be partly caused by their reduced relative strength, as this was significantly correlated with hop distance (0.576; $p<0.01$).

The pattern of ACLR having intermediate hop performance between ACLD and CONT has not previously been shown. Our findings that d_{hop} was reduced in ACLD was in agreement with previous studies (Gauffin et al., 1990; Scavenius et al., 1999; Button et al., 2006; Gustavsson et al., 2006; van Deursen and Phillips, 2006). The reduced d_{hop} in ACLR was in agreement with Orishimo et al. (2010) but not Gokeler et al. (2010).

To investigate recovery of landing strategies, TIP analysis was used to evaluate sagittal plane kinematics and kinetics. This analysis (Fig. 2) showed that ACLD used a more pendular strategy than ACLR and CONT as they used reduced knee flexion/extension range of motion (ROM_{knee}) throughout landing (Table 3). This pendular strategy coincided with decreased knee extensor moments and increased hip flexion and plantar flexion moments. CONT used a more telescopic strategy with a greater ROM_{knee} and a larger $M_{knee(max)}$ (Table 3). ACLR also seemed to use a more telescopic strategy but performed the hop with a significantly smaller $M_{knee(max)}$ than CONT (Table 3). ACLD relied on a more pendular strategy with reduced peak knee extensor moments. They landed in a more upright posture which is a disadvantage as it leads to limited opportunities to decelerate the COM. This constraint could explain that they did not show a reduced t_{dec} despite a reduced d_{hop}. With TIP analysis we were able to explain and advance earlier findings. We demonstrated that sagittal plane control during landing was intermediate in ACLR between ACLD and CONT. It suggests that ACLR rehabilitation has not resulted in complete recovery.

Most of our findings on sagittal plane control of hop landing were in agreement with previous findings in literature. The reduced ROM_{knee} in ACLR was in agreement with Orishimo et al. (2010) and Deneweth et al. (2010), but not with Gokeler et al., (2010). In ACLD, Rudolph et al. (2000) observed that low functioning individuals used a smaller range of knee flexion, smaller knee extensor moments and a greater contribution from the hip to the total support moment. Oberländer et al. (2012) also found that ACLD performed a hop using higher moments at the ankle and hip compared to CONT. In an earlier study van Deursen and Phillips (2006) showed that the landing technique during a run and stop task was adapted in ACLD compared to healthy subjects and that ACLD used a knee avoidance technique. Their findings with reduced knee extension and increased hip flexion and plantar flexion moments agreed with our findings for a single leg hop. These findings collectively support our conclusion that ACLD used a more pendular strategy, which coincides with a smaller ROM_{knee} and $M_{knee(max)}$ and larger $M_{hip(max)}$ and $M_{ankle(max)}$ than ACLR and CONT.

We investigated medio-lateral control and coronal plane kinetics. In respect of medio-lateral control, knee movement was least fluent in ACLD, intermediate in ACLR and most fluent in CONT (Table 4). Peak displacement of the knee ($D_{knee(max)}$) showed a similar relationship, with the largest knee displacement medial relative to the ankle in ACLD and the smallest in CONT. At the peak extensor moment the knee was however at a similar position relative to the ankle in all groups. The knee movement was less fluent in the ACL patients and showed larger medio-lateral excursions, which is interpreted as a sign of lack of knee control. Either they were unable to provide sufficient motor control for an external adductor moment of the same magnitude as in CONT, or it could be interpreted as a protective strategy to avoid challenging adductor moments altogether. Although the peak knee moments were reduced, the lack of control could arguably result in loading of the articular cartilage on locations that are normally not loaded in such a manner and this presumed altered loading could have implications for early development of osteoarthritis (Blagojevic et al., 2010). Our study is the first to demonstrate that knee control was not fully recovered in ACLD and ACLR. There is no previous literature evaluating coronal plane control of the knee during single leg hop in ACL patients.

This study had several limitations mostly related to the clinical sample of ACL participants. The CONT group had a larger proportion of females than the ACLD and ACLR groups. We have investigated thoroughly whether this could have influenced our findings. The main gender differences are due to height and mass and we therefore normalized our outcome variables to body height and weight to account for the gender differences. It could be expected that if the groups were perfectly matched with a larger proportion of male subjects in the CONT group their mean maximum hop distance would have been increased, which would have exaggerated our results and increased significance. This would however not affect our main conclusions. Another limitation was that the ACL injured patients had other accompanying injuries besides ACL rupture. The typical population of patients seen in the hospital setting however has a mixed combination of injuries and an ACL injury hardly ever occurs without at least some comorbidity. The participants in this study also had a relatively wide range according to time since injury and surgery. These are however the ones typically seen in the clinical setting. A proportion of the ACLD participants (20%) were unable to hop and could not be included in the analysis. Therefore those ACLD that were included in the analysis were a subset of better performing ACLD individuals. Because of this some of the conclusions regarding ACLD could have been underestimated, as in that they were performing better as a group as would be expected. In spite of that effect we still found significant differences, which emphasizes that between group differences were present.

Current clinical practice uses hopping distance to evaluate recovery of ACL patients. This study demonstrated that to improve treatment outcome other aspects need to be evaluated, such as movement strategies and medio-lateral knee control. Neuromuscular control and perturbation exercises are already recommended but need to be further developed. To optimize control of knee joint loading a telescopic deceleration strategy could be promoted by early introduction in less demanding tasks such as one legged squat, before progressing to more dynamic tasks. This may be enhanced by developing novel rehabilitation techniques that target fluency.

This study showed that ACLD and ACLR patients had not recovered landing strategies and medio-lateral knee control. This altered control may result in altered stresses within the knee that could result in further damage and early onset osteoarthritis. ACL rehabilitation better targeted at medio-lateral knee control could improve treatment outcome.

Conflict of interest statement

There is no conflict of interest for any of the authors.

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