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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.

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