Leg asymmetry and muscle function recovery after anterior cruciate ligament reconstruction in elite athletes: a pilot study on slower recovery of the dominant leg

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ABSTRACT: The aim of this study was to examine performance in hopping tests in male athletes after anterior cruciate ligament reconstruction (ACLR) in the 4-to-6 months post-surgery period. A total of 36 athletes (24 ACLR and 12 controls) participated in this study. The ACLR group consisted of athletes who had undergone an ACLR on their dominant side (ACL DG n=16) or non-dominant side (ACL NDG n=8). Participants completed the following functional tests: a single-leg hop (SLH), single-leg triple hop (SL3H) and single-leg counter movement jump (SLCMJ), then the limb symmetry index (LSI) was calculated. There were no significant differences between the dominant and the non-dominant legs for all functional tests when comparing the ACL DG and the ACL NDG at 6 months after surgery. At 6 months after ACLR, the LSI of the two legs was within acceptable values, whether the athlete had the operation on their dominant or non-dominant leg (except the mean LSI for the ACL DG in the SLCMJ test). Furthermore, the control group showed higher performances as compared to the ACL group for all variables at 6 months after surgery, despite acceptable LSI. We concluded that an early return to "full participation to training" is not recommended in participants who have undergone an ACLR with patellar tendon grafts.

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INTRODUCTION

Anterior cruciate ligament (ACL) lesions are common among athletes [1]. The primary goal of ACL reconstruction (ACLR) surgery is to re-establish knee joint stability, regain normal levels of activity and return to pre-injury levels of performance [2]. Neuromuscular impairments resulting in quadriceps strength deficits are common after ACLR [3], which may contribute to functional impairments [4]. Deficits are due to a suboptimal recovery process [5] and neural factors [6].

This is particularly concerning given the high demands placed on the knee joint during high-intensity sport activity and may help to explain the risk of secondary ACL rupture that is approximately three-fold higher compared with the risk of ACL rupture in healthy uninjured adults [7].

Muscle activation, functional activities, and strength have previously been evaluated after ACLR [8] and some studies have evaluated the pattern of strength and functional recovery during the 4–6 months post-ACLR period [2]. This period is important because at four months after surgery, depending on the rehabilitation protocol, functional training begins to include exercises and drills that are relevant to the athlete's sport [9, 10, 11, 12].

To advance to this stage, the athletes are supposed to achieve (i) criteria related to athletic power development and symmetry [13, 14] and also (ii) full range of motion without pain or effusion [15]. With objective measures setting, it is easier and safer for therapists to allow their patients to progress to further stages of the rehabilitation programme [13].

Further, it has been suggested that, at six months, most athletes are supposed to resume their "full participation in training" and should be able to complete most activities or even compete in their sport [1, 16, 17].

However, this timeframe has recently been questioned, as the risk of sustaining an ACL re-injury is highest during the early period (6–12 months) of return to sport (RTS) [18, 19]. In this regard, Grindem et al. [18] stated that post-surgical time alone is not sufficient to determine readiness for RTS [18]. The difficulty with determining the moment of return to play (return to full participation in competitions) is that it is still unknown which of the measures should be used to predict a safe return to play with a low risk of a subsequent ACL injury [20].

Functional tests such as the single leg hop (SLH) and single leg triple hop (SL3H) [21, 23] and a single leg countermovement jump (SLCMJ) may be used to evaluate knee function in those who have previously undergone ACLR. In addition to these tests requiring minimal space, time and equipment [21], each leg can be evaluated independently, and asymmetries may be subsequently identified [21]. The injured knee joint should be equivalent to its contralateral side with respect to range of motion, strength, and function with no, or a minimal amount of swelling [11]. The limb symmetry index is used to assess whether muscle strength and lower limb functional performance are ideal or not, and is used as an important criterion for allowing the patient to return early to sport [10, 23, 24]. Logically, deficits in lower limb strength and function have been reported to affect the ipsilateral side to a greater degree when compared to the contralateral side after rehabilitation [25]. The post-injury reduction of strength and muscle function is mainly due to subsequent inactivity and induced muscle atrophy [12]. However, some authors have shown that this phenomenon may actually be bilateral [26]. When the injured leg recovers, the uninjured contralateral limb detrains and is therefore simultaneously affected [27].

Most studies have examined the contralateral limb when evaluating changes in strength and functional performance following ACL injury [27, 28]. Interestingly, some authors have reported that pre-injury differences may exist in muscle function and this may be related to limb dominance [24, 29]. Asymmetry due to limb dominance implies that the effect of an ACL injury depends on the leg dominance [30]. Consequently, improving strength, normalizing leg strength symmetry [13] and aiming at the restoration of symmetrical and normal movement pattern remains an important goal after ACLR [31]. In addition, ACLR athletes should achieve symmetrical bilateral power between the injured leg and the uninjured leg, indicated by a difference less than 15% [22]. It is important to note that depending on the measure and on the muscle group assessed, there is probably no athlete who is perfectly symmetrical [32]. Instead of aiming at perfect symmetry, which is probably utopic, one should focus on reaching symmetrical normal ranges (usually between 10 and 15% in the literature) [9, 22, 33, 34]. Reaching a minimal symmetrical index of 15% will be accompanied by reduced strength differences between legs [27] and may contribute to restarting physical activities, such as walking and jogging, as well as progressively returning to the practice of their sport [28].

Despite the identification of limb asymmetry, it is somewhat difficult to assess the primary cause of abnormal function in injured participants (e.g., strength and/or balance deficits). If differences in neuromuscular control exist between the dominant and non-dominant legs, this may have important implications for specific training and rehabilitation of athletes [27]. The primary aim of the study was therefore to examine functional performance in a single leg-hopping and jumping tests in male athletes after ACLR in the 4–6 months post-surgery period. The effect of leg dominance was also considered when addressing this aim.

MATERIALS AND METHODS

Participants

A minimum sample size of 36 was determined from an "a priori" statistical power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) [35]. The power analysis was computed with an assumed power at 0.80 at an alpha level of 0.05, an effect size of 0.9 and allocation ratio N2/N1=2.

A total of 36 male elite athletes participated in this prospective cohort study. Participants were divided into two broad groups: an experimental (n=24) and a control group (n=12). The control group (CG) was composed of athletes who practised team sports (right-leg dominant for 9 out of 12). The athletes of the experimental group (ACLG) practised team sports (n=5) and combat sports (n=19). This group was further split into two groups: a/ participants who had undergone ACLR on their dominant side (ACL DG: n=16); eight of them with right dominant leg; and b/ participants who had an ACLR on their non-dominant side (ACL NDG: n=8); three out of 8 had a right dominant leg (Figure1).

The dominant side was defined as the preferred leg with which the player kicked a ball [36]. The characteristics of the participants are outlined in Table 1.

All participants in the two experimental groups had a unilateral injury and ACLR with a patellar tendon graft. Patients with concomitant damage to the collateral ligaments or menisci were not included in the study.

Further, they had no evidence of knee effusion, no limitations in knee range of motion, were able to hop on the injured leg without pain and had no previous injury related to the lower extremities. For participants in these two groups, the rehabilitation process was supervised by the same group of six physiotherapists who were employed at a single centre. The functional training programme for ACL patients included: a variety of exercises designed to specifically increase neuromuscular control, muscle strength, proprioception, speed, and agility of the lower limbs [9].

Prior to testing, each participant gave informed consent after being provided with an explanation of the experimental procedures, as well as the possible risks and benefits of the study. Permission to

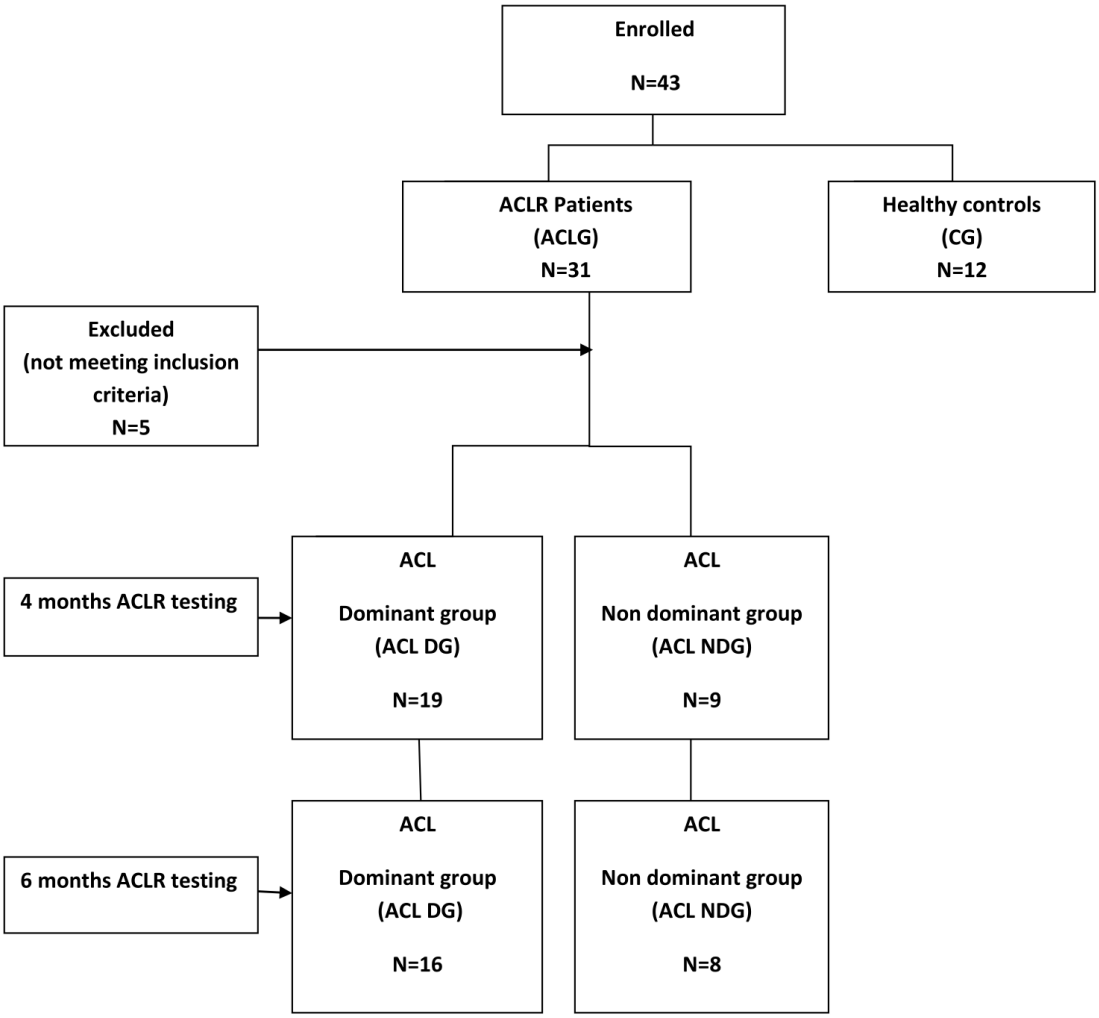

FIG. 1. Flow chart of study participants.

TABLE 1. Characteristics of the participants at 6 months post-surgery (Mean, SD)

Variables	ACL DG (n=16)	ACL NDG (n=8)	CG (n=12)	P
Age (years)	21.4 (3.5)	23.2 (4.92)	23.6 (2.77)	0. 29
Height (m)	1.78 (0.08)	1.84 (0.05)	1.77 (0.05)	0. 08
Body mass (kg)	74.8 (8.5)	78.3 (4.3)	73.1 (6.5)	0.28
Body mass index (kg/m^2)	23.5 (1.5)	23.1 (1)	23.4 (1.4)	0.64
Time from injury to surgery (weeks)	11.6 (7.7)	12.6 (14.7)	N/A	0.07
Time from surgery to rehabilitation (weeks)	3.1 (1.7)	2.2 (1.5)	N/A	0.73
Sport practice (Football/Other) (hrs/week)	11/5	6/2	7/5	0.32
Mechanism of injury (contact/no contact)	10/6	4/4	N/A	1
Presence of partial meniscal repair	2/16	0/8	N/A	1

ACL=anterior cruciate ligament, ACL DG=dominant group; ACL ND=non dominant group; CG=control group. SD=standard deviation.

conduct the study was provided by the local Clinical Ethics Committee of the National Center of Medicine and Sciences of Sport. The study was conducted according to principles outlined by the Declaration of Helsinki [37].

Procedures and data collection

For the experimental groups testing was conducted in three sessions: 1) characteristics of participants, 2) pre-test (4 months after surgery) and 3) post-test (6 months after surgery). For the control group there were two testing sessions only (characteristics of participants and baseline testing). No follow-up testing was conducted with the control group.

A single leg hop (SLH), single triple leg hop (SL3H) and a single leg counter movement jump (SLCMJ) test were conducted bilaterally. The reliability and the validity of these tests has previously been proven [21]. Each of the tests was performed three times and the best trial was used for further analysis. For each test, participants from the experimental groups performed the first trial with the uninjured leg, followed by the injured side. For the control group, participants started with the dominant leg. Each of the hop/jump testing sessions involved a warm-up of 20 minutes (including jogging, stretching and lower limb exercises). All tests on the same side were separated by three minutes and a one-minute rest period was given when testing was transferred to the opposite leg.

As well as being reported as absolute values for each side, hop/jump data were as reported as relative values using the limb symmetry index (LSI). The LSI is calculated as the mean score of the involved (or non-dominant) leg divided by the mean score of the uninvolved (or dominant) leg, with the result multiplied by 100. The LSI was calculated as:

$$LSI = (\text{non-dominant/dominant leg}) \times 100.$$

An LSI score >85% is considered as acceptable and >115% as abnormal [22, 38].

Statistics

Descriptive data (mean±SD) were calculated for all participants' characteristic data (age, height, body mass and body mass index) and for all functional tests (SLH, SL3H and SLCMJ). All data were initially analysed using Microsoft Excel (Microsoft, Redmond, Washington). Test-retest reliability of each test (and side) was determined by the intraclass correlation coefficient (ICC) with a 95% confidence interval and the standard error of measurement. The ICC formula was selected because the values representing each single leg test were the mean of three measures.

Comparisons between the experimental and the control groups were made using Student's independent t-tests for the hop (SLH, SL3H) and jump (SLCMJ) data. Two-way (group vs. Time: ACL DG and ACL NDG × four and six months) analysis of variance with repeated measures determined whether there was an improvement in distances (SLH, SL3H) and height (SLCMJ) data. Where appropriate, pairwise comparisons using Bonferroni corrected methods were used. The magnitude of the differences between limbs was calculated with eta squared to evaluate effect sizes. Eta-squared values of 0.01, 0.06 and 0.15 were considered to represent small, medium and large differences, respectively [39]. Differences in frequencies between the number of athletes who achieved normal LSI values were calculated using the chi-squared test. The above statistical analyses were completed using SPSS v 20 (SPSS; IBM Corp, Armonk, New York). The level of significance was set at $p \leq 0.05$.

TABLE 2. Reliability of the tests employed in this study

Pooled data (pre-test plus post-test, all groups)	ICC (inter-participant reliability)		Intra-participant reliability	SEM
	ICC	95% Confidence interval		
SLH				
– D leg	0.98	0.97–0.99	0.95	4.4 cm
– ND leg	0.98	0.96–0.99	0.93	2.5 cm
SL3H				
– D leg	0.99	0.98–0.99	0.85	13.5 cm
– ND leg	0.99	0.99–0.99	0.96	9.6 cm
SLCMJ				
– D leg	0.93	0.90–0.96	0.84	0.8 cm
– ND leg	0.93	0.88–0.96	0.82	0.7 cm

ICC=intraclass coefficient.; SEM=standard error of measurement; SLH=single leg hop, SL3H=single leg triple hop; CMJ=countermovement jump; D=dominant; ND=non dominant.

RESULTS

The inter-participant reliability (ICC) of the three single leg functional tests (SLH, SL3H and SLCMJ) performed on both sides was considered as excellent (Table 2).

Dominant versus non-dominant ACL groups

No significant between-group differences were found for age, mass, height or body mass index (Table 2). Further, no significant differences were found between the ACL DG and ACL NDG for the SLH, SL3H and SLCMJ tests conducted with the injured and uninjured legs at six months after surgery. However, when comparing the improvement between four and six months, both the ACL DG and ACL NDG showed increased performance ($p<0.001$) with both legs (medium and large eta squared) for all tests, except for the SLCMJ performed with the uninjured leg (Table 3). Significant interactions (leg x time) were found for all tests ($p<0.001$), with large eta-squared values for the SLH, SL3H and SLCMJ ($\eta^2=0.6$, $\eta^2=0.53$,$\eta^2=0.2$) respectively. However, no group effects were found ($p>0.05$).

The percentage of participants who achieved LSI values greater than 85% on SLH and SL3H increased over time from 4 to 6 months after ACLR in the two groups but significant differences were observed only for the SL3H. However, differences between the ACL DG and the ACL NDG were observed for the SLCMJ. In addition, at 6 months, all mean LSI values were greater than 85% but not for the ACL DG in the SLCMJ test (Table 4).

ACL reconstructed dominant and non-dominant versus healthy participants at 6 months after surgery

Significant differences were evident between ACL DG compared to control DG for all the tests. However, there were no differences between ACL NDG and control NDG for all tests except in the SL3H ($p<0.05$). The CG showed higher performances as compared to the ACLG for all variables at 6 months after surgery (Table 5).

Using a 15% cut-off value for the lower LSI, a large proportion of ACL patients were identified as acceptable during SLH and SL3H. For the single leg CMJ, the LSI performances of both groups were

TABLE 3. Hop/jump testing and thigh circumference values at four and six months post-surgery (Mean, SD)

Variables	Group	4months Post-Surg.	6months Post-Surg.	%Progress	Effect- time	Effect-group	Interaction
SLH (m)	ACL DG	1.81 (0.15)	1.91 (0.12)**	7 (7.71)	29.7**	1.8	1.7
	ACL ND	1.82 (0.18)	2.04 (0.1)**	10.2 (7.5)	$\eta^2=0.6$	$\eta^2=0.07$	$\eta^2=0.07$
SL3H (m)	ACL DG	6.03 (0.42)	6.31 (0.5)**	4.3 (8.07)	24.8**	1.02	5.12*
	ACL NDG	6.05 (0.38)	6.62 (0.3)**	10.9 (3.52)	$\eta^2=0.53$	$\eta^2=0.04$	$\eta^2=0.2$
SLCMJ(m)	ACL DG	0.31 (0.33)	0.32 (0.4)	7.4 (18.4)	4.7*	3	0.15
	ACL NDG	0.3 (0.31)	0.33 (0.3)*	8.7 (7.9)	$\eta^2=0.2$	$\eta^2=0.1$	$\eta^2=0.007$
Circ (0cm)(m)	ACL DG	0.05 (0.11)	0.11 (0.02)	83 (81.9)	3.48**	0.6	0.25
	ACL NDG	0.03 (0.04)	0.06 (0.02)	80.6 (77.6)	$\eta^2=0.1$	$\eta^2=0.02$	$\eta^2=0.01$
Circ (+10cm)(m)	ACL DG	0.12 (0.12)	0.83 (0.01)	39.1 (31.2)	14.3*	0.6	0.23
	ACL NDG	0.22 (0.11)	1.12 (0.01)	37.5 (36.8)	$\eta^2=0.4$	$\eta^2=0.02$	$\eta^2=0.01$
Circ (+15cm)(m)	ACL DG	0.11 (0.11)	0.91 (0.1)	34 (24.1)	5.49	1.28	1
	ACL NDG	0.21 (0.13)	1.61 (0.1)	9 (9.3)	$\eta^2=0.2$	$\eta^2=0.05$	$\eta^2=0.04$

SLH=single leg hop, SL3H=single leg triple hop; SLCMJ=single leg countermovement jump; Circ=Circumference*Significant difference ($p<0.05$) and **Significant difference ($p<0.01$) between 4 and 6 months. SD=standard deviation.

TABLE 4. Percentage of athletes who achieved greater than 85% on the limb symmetry index

	SLH	SL3H	SLCMJ
	ACL DG (16)/ACL NDG (8)	ACL DG(16)/ACL NDG(8)	ACL DG (16)/ACL NDG(8)
4 Months	43.5 (7) vs 62.5 (5)	37.5 (6) vs 37.5 (3)	37.5 (6) vs 75 (6)
6 Months	82 (13) vs 87.5 (7)	82 (13)* vs 100* (8)	37.5 (6) vs 87.5 (7)+

SLH=single leg hop, SL3H=single leg triple hop; CMJ=countermovement jump; *Significant difference ($p<0.05$) between 4 to 6 months; + significant difference ($p<0.05$) between ACL DG and ACL NDG.

TABLE 5. Measures for dominant and non dominant legs for ACLG and healthy control (Mean, SD)

Variables	ACL DG (n=16)	Control DG (n=8)	ACL NDG (n=12)	Control NDG (n=12)
SLH (m)	1.78 (0.20)	2.06 (0.15)**	1.89 (0.13)	1.99 (0.17)
SL3H (m)	5.83 (0.63)	6.73 (0.75)**	6.09 (0.44)	6.59 (0.41)*
SLCMJ (m)	0.26 (0.38)	0.30 (0.34)*	0.28 (0.33)	0.29 (0.38)
Circ (0cm) (m)	0.01 (0.02)	0.02 (0.04)	0.06 (0.01)	0.02 (0.04)
Circ (10cm) (m)	0.08 (0.01)	0.06 (0.06)	0.01 (0.01)	0.06 (0.06)
Circ (15cm) (m)	0.09 (0.09)	0.06 (0.05)	0.01 (0.09)	0.06 (0.05)*

SLH=single leg hop, SL3H=single leg triple hop; SLCMJ=countermovement jump; Circ=circumference; ACL DG=ACL dominant group; Control DG=dominant control group; ACL NDG=ACL non dominant group; Control NDG=non dominant control group. ACLG=anterior cruciate ligament group; * Significant difference between groups ($p < 0.05$); ** Significant difference between groups ($p < 0.001$).SD=standard deviation. ACL DG vs Control DG and ACL NDG vs. Control NDG.

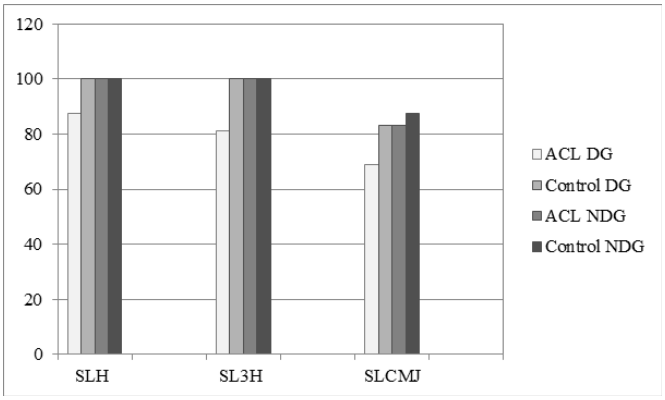

FIG. 2. Leg symmetry index (LSI) for ACLG and controls groups at 6months
SLH=single leg hop, SL3H=single leg triple hop; SLCMJ=single leg countermovement jump; ACL DG=ACL dominant group; ACL NDG=ACL non dominant group.

lower than 87.5%. With respect to the ACL patients, the ACL NDG had a higher percentage of participants who had acceptable LSI values when compared to the ACL DG for the SL3H at 6 months after surgery (Figure 2).

DISCUSSION

The main finding of this study was that performances with both dominant and non-dominant limbs were similar during unilateral hopping and jumping tests six months after ACLR, resulting in a normal symmetry index. However, higher performance values were observed in the CG as compared to the ACLG for all variables at 6 months after surgery especially for the dominant injured leg.

If a difference in neuromuscular control exists between the dominant and non-dominant legs, after ACLR this may have implications for rehabilitation of athletes. The functional recovery after ACLR depends on the rehabilitation process to capture important clinical changes [40] and was not influenced by limb dominance.

Similarly, Ostenberg et al. [41] found no between-leg differences in the SLH test after ACLR but side-to-side differences were observed in other anatomical characteristics of the lower extremity, e.g. quadriceps angle and tibial torsion [30].

This finding was however not in accordance with the study of Strandberg et al. [27] where differences were found in muscle size between right and left legs. In the latter study, the majority of the patients were right leg dominant, and the muscles of their right legs were bigger than those of the left leg after ACLR.

Another explanation for observing similar strength in the dominant and non-dominant legs is the potential poor discrimination specificity of the hopping test as an assessment tool after ACLR. Therefore, muscle function tests used as a parameter to guide rehabilitation may not be sensitive enough and therefore could be questioned. Based on these results, sophisticated testing equipment could be used, for example isokinetic testing. Nevertheless, in the field the ecological validity of isokinetic testing is questionable, while functional tests remain very close to a real sport setting [16, 42].

On the other hand, Wang et al. [17] showed that individuals with an ACLR on the dominant side developed significantly different patterns of movement at the knee joint when compared to those with an ACLR having been performed on the non-dominant side. It could be speculated that different compensatory motion patterns are developed between ACL DG and ACL NDG.

In addition, Wang et al. [17] suggested that natural mechanics could be responsible for asymmetry in able-bodied walking, rather than neurophysiological mechanisms such as leg dominance. In a single practice session, certain athletic movements can be repeated

hundreds of times. The dominant leg would be expected to be used more (e.g. while shooting in football players) and the repetition in quadriceps activity can lead to muscular imbalances between limbs [43]. In this context, it has to be mentioned that when the dominant leg of football players shoots the ball with dynamic and powerful contractions, the contralateral non-dominant leg is solicited in a different way, by insuring body stability thanks to isometric contractions. The use of such different exercise patterns over and over again during activity could explain some of the differences that some could observe between both limbs in asymmetrical sports.

Also absolute strength is a more important factor influencing bilateral strength asymmetry [38]. These motion changes could alter the normal contracting and loading on articular cartilage, which may contribute to the development of knee osteoarthritis [17]. Asymmetric knee angles, knee moments, and knee power profiles have also been observed after injury and may persist six months after surgery despite participants achieving symmetrical quadriceps strength [25].

The present study showed that between four and six months after surgery, the ACL DG and the ACL NDG had good improvements in all tests. These results are consistent with previous studies [9, 10, 40]. The tests used in the present study can be used to assess functional performance in a recently injured limb [22] and will test muscular strength, neuromuscular adaptation, as well as joint stability in the lower limb [33].

At the late stage of rehabilitation, the injured leg muscle performance score differences should be minimized and should approximate the contralateral side [10].Normal proportions have been reported as ≥ 85%, i.e. the operated leg being within 85% of the healthy one [22, 33].In the present study, limb-to-limb asymmetries were reduced from 4 to 6 months after surgery, and LSI values were restored to ≥ 85% after training and more than 82% of injured participants had an acceptable LSI value during SLH and SL3H tests for both groups [24]. By contrast, Wilk et al. [26] found that only 43% of the studied participants had an LSI score higher than 85% by 6.5 months after surgery. In the present study, the high proportion of participants reaching acceptable values of LSI during the SLH test indicates that improvements in LSI can occur from 3 to 6 months after ACLR [44] and early restoration of quadriceps strength can result in better functional outcomes in participants after ACLR with patellar tendon grafts [2]. Probably, symmetry is also easier to achieve when the uninjured leg is weak. Therefore, one should take into consideration this when interpreting the LSI scores for a decision to RTS.

However, the single leg CMJ test showed that for the ACL DG, only 37.5% of participants had acceptable values up to 6 months after ACLR. These results are in agreement with those of DeJong et al. [2], who found an LSI score below the "safe range" value for 31% of the participants at a later stage. This is also supported by several studies that indicate a delay in athletes achieving 90% single leg vertical jump height symmetry when compared to horizontal hopping after ACLR [45]

In the mid stage of the rehabilitation programme, the athlete must achieve a single limb hop for distance that falls within 15% of the uninjured side to be able to advance to the next stage [13]. The LSI values are often used as cut-off scores for RTS and have been the most frequently reported criterion for assessing whether muscle strength and hop performance are acceptable or not, i.e. that the capacity of the injured leg is, or is not, as good as that of the uninjured leg. [8].

A recent study showed that at 6 months, the hop test could predict return to previous levels of sport at 2 years after surgery [46] and that patients with SLH and SL3H scores greater than 85% LSI at the time of RTS were more likely to return to their previous performance levels [47].

More recent evidence indicates that re-injury rates can be reduced by 50% for every month if the return to sport is delayed up to 9 months [20]. Grindem et al. [18] employed an RTS test battery that required patients to score >90% LSI for quadriceps strength and functional hop capacity, and demonstrated that the re-injury rate was higher for patients who RTS without meeting objective cut-offs.

There remains no clear consensus regarding ideal cut-off scores for hop tests [48]. The different cut-off-scores for LSI for SLH tests may be questioned for their sole use as a criterion for RTS after ACLR and should therefore be used with caution [49]. Measuring only hop distance, even using the healthy leg as a reference, is insufficient to fully assess knee function after ACLR [50]. Moving forwards, other factors relating to neuromuscular/movement control (as an additive to just hop distance/time) should be examined and form part of the RTS decision-making process [42].

It has previously been shown that muscle function tests are strong determinants for between-limb asymmetry predictions in ACLR [23]. Recently Bailey and colleagues [51] demonstrated the effects of strength asymmetry and/or limb preference on dynamic athletic movements such as jumping, running and kicking. Also, it has been demonstrated that strength asymmetry of >15% resulted in a reduced jump height [38]. Therefore, the cut-off threshold of 85% seems strengthened by the latter findings.

Studies have demonstrated asymmetry in athletes during athletic tasks such as jumping, kicking tasks, and resistance training, along with clinical strength assessment tasks [38]. Attainment of appropriate limb symmetry may reduce osteoarthritis, risk of further injury and contribute to walking and jogging patterns similar to uninjured participants [11].

When comparing healthy participants (CG) to the ACLG, we found differences in parameters for the dominant leg. Control DG subjects had better performances in hopping tests than the ACL DG at 6 months after surgery. Performance may be affected by bilateral function and strength deficits and may put athletes at a disadvantage when compared to their peers. The existence of knee function deficits after ACLR may have significance for subsequent re-injury [22]. In that regard, athletes may demonstrate decreased muscular strength and postural stability for 6 months to 2 years after reconstruction [23].

In addition, athletes may feel a psychological hindrance such as fear of re-injury [52], negatively impacting their readiness to overcome functional challenges. Health practitioners should consider carefully the return to full participation and "restricted training or competition". The results of this study should be used to counsel participants about their expected functional recovery and to optimize rehabilitation. Also, accelerated rehabilitation programmes appear to be getting phased out, with a return to 9–12-month full RTS protocols [53]. Indeed, the present study investigated the effect of a faster pace protocol, showing promising results. We do not know if the participants had successful RTS, any re-injury or progression of osteoarthritis in the long run. In this regard, as a recent study indicated that re-injury rates can be reduced by 50% for every month when the return to sport is delayed up to 9 months [18], we draw the attention of the reader about the risk of resuming competition too early, and even resuming an intensive training load too early. Further studies are necessary to study the safety of any intensive rehabilitation programme on the health of the athletes.

ACL NDG had similar hop performances to the control NDG at 6 months after surgery. This result suggests that muscle function was significantly improved in the ACL NDG when compared with the matched CG. Another suggestion that could be advanced is that the non-dominant leg has a predominantly postural function in daily life, which could probably lead to better postural stability of the so-called standing leg [54]. Unilateral hop may not assess potential unloading of the injured leg during daily living activities, which predominantly are performed bi-laterally. ACL patients are known to reduce loading levels in the injured knee during various types of functional motor tasks [28]. This pattern of limb unloading may be due to mechanical and/or muscular limitations and/or an adapted motor strategy to protect the injured leg.

In the control group, no differences were found when comparing the SLH, the SL3H and the single leg CMJ distance between the dominant and the non-dominant legs [55]. These results are consistent with those of Greenberger and Yanci [5, 55]. However, other studies showed that asymmetry may exist in healthy participants [56] (i.e. legs in the impulse phase CMJ variables) [55]. Many individuals may fail to realize that some sports have specific asymmetries that may be advantageous to performance, and the exact profiles for establishing injury risk related to asymmetry have yet to be developed for particular sports [56].

Some athletes could have a visible limb imbalance [30], while others show an absence of imbalance between limbs [57]. Such discrepancies might be explained by some methodological differences, such as leg strength and initial injury level [57].

The laterality index was in the range of that of the control group. This suggests that from a laterality prospective the participants of the experimental group were performing well. Nevertheless, the laterality index is a relative measure comparing the operated leg to the contralateral one. It has to be stressed that the absolute strength values could be weak even if the laterality index is normal. This is probably due to the fact that while the operated leg is in rehabilitation, the contralateral leg detrains at the same time. This strongly suggests that patients in rehabilitation should consider cross training (training of the healthy leg) [57].

There were limitations in the present study. Firstly, the cohort includes a relatively limited number of participants and may not be large enough to provide definitive results for all of the studied comparisons. In addition, leg dominance is a challenging definition that may induce some confusion when used in clinical screening procedures. Since asymmetry was defined as side-to-side differences, the use of different cut-points (normal ratios) as greater than or equal to 85% [10, 38] or 90% [39] render direct comparisons between studies difficult.

Another limitation is that the contralateral leg is often used for evaluating the effects of ACL injury and for monitoring the rehabilitation process while it is obvious that this "healthy leg" is affected by detraining along with the injured leg. Also, data regarding preoperative muscle strength and knee function during testing were not available to provide more information on improvements from baseline to 6 months after ACLR.

Finally, athletes from various sports (team sports vs individual sports) participated in the study. However, the reported differences between different sports fall well within the standard deviations of the proposed normative values, making them clinically irrelevant.

CONCLUSIONS

In conclusion, the present study showed that functional performances of both dominant and non-dominant limbs were similar during the hopping tests at 6months after surgery. At 6 months after ACLR, limb-to-limb asymmetries were reduced, and a normal LSI was restored with the training programme used in the present study for the non-dominant leg. For the dominant injured leg some delay in the recovery of functional strength is apparent in one of the used tests. We therefore suggest that future studies should focus on the time course of the dominant and non-dominant legs' recovery after ACLR, with special focus on the dominant leg, which seems to deserve special attention when it is affected by an ACLR.

An early return to "full participation in training" is not recommended in participants who have undergone an ACLR with patellar tendon grafts. Delaying RTS of course allows more time to achieve the necessary functionality; however, this is only effective if this time is filled with high-quality rehabilitation. It would appear more logical to optimise our rehabilitation strategies after ACLR.

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Conflict of interests

The authors declared no conflict of interests regarding the publication of this manuscript.

REFERENCES

1. Beynnon BD, Bennjamin S, Johnson RJ, Abate JA, Nichols CE, Fleming BC, Poole A. Roos H. Rehabilitation after anterior cruciate ligament reconstruction. A prospective, randomized, double-blind comparaison of programs administrered over 2 different time intervals. Am J Sports Med. 2005;33(3):347–359.
2. DeJong SN, Van Caspel DR, Van Haeff MJ, Saris, DBF. Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. Arthroscopy. 2007;23:21–28.
3. Pamukoff DN, Pietrosimone BG, Ryan ED, Lee DR, Blackburn JT. Quadriceps function and hamstrings co-activation after anterior cruciate ligament reconstruction. J Athl Train. 2017; 52:422–428.
4. Kuenze C, Hertel J, Saliba S, Diduch DR, Weltman A, Hart JM. Clinical thresholds for quadriceps assessment after anterior cruciate ligament reconstruction. J Sport Rehabil. 2015;24:36–46.
5. Greenberger HB, Paterno MV. Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. J Orthop Sports Phys Ther. 1995; 22:202–6.
6. Johnson AK, Riann M. Palmieri-Smith, Lindsey K, Lepley ATC. Contribution of Neuromuscular Factors to Quadriceps Asymmetry After Anterior Cruciate Ligament Reconstruction. J Ath Train. 2018;53(4):347–354.
7. Salmon L, Russel V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. Arthroscopy. 2005;21:948–57.
8. Thomee R, Kaplan Y, Kvist J, Myklebust G, Risberg MA, Theisen D, Tsepis E, Werner S, Wondrasch B, Witvrouw EI. Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2011; 19:1798–805.
9. Souissi S, Wong DP, Dellal A, Croisier JL, Ellouze Z and Chamari K. Improving functional performance and muscle power 4–to-6 months after anterior cruciate ligament reconstruction. J Sports Sci Med. 2011;10: 655–664.
10. Myer GD, Paterno MV, Ford K, Nick TG, Hewett TE. The effects of generalized joint stability on risk of anterior cruciate ligament injury in young female athletes. Am J Sports Med. 2008;36:1073–80.
11. Shelbourne KD and Klotz C. What I have learned about the ACL: utilizing a progressive rehabilitation scheme to achieve total knee symmetry after anterior cruciate ligament reconstruction. J Orthop Sci. 2006;11:318–325.
12. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. Clin Sports Med. 2008;27:405–424.
13. Myer, GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria based progression through the return to sport phase. J Orthop Sports Phys Ther. 2006; 36,385–402.
14. Logerstedt D, Grindem H, Lynch A, Eitzen I, Engebretsen L, Risberg MA, Axe MJ, Snyder-Mackler L. Single-legged hop tests as predictors of self reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo cohort study. Am J Sports Med. 2012; 40(10):2348–56.
15. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. Sports Med. 2004;34:269–280.
16. Paul DJ and Nassis GP. Testing strength and power in soccer players: the application of conventional and traditional methods of assessment. J Strength Cond Res. 2015; Jun, 29 :1748–58.
17. Wang H, James E, Fleischli B, Zheng A. Effect of lower limb dominance on knee joint kinematics after anterior cruciate ligament reconstruction. Clin Biomech 2012; 27: 170–175.
18. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. Br J Sports Med 2016; 50(13):804–808.
19. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. Br J Sports Med 2016; 50(15):946–951.
20. Van Melick N, van Cingel REH, Brooijmans F, Neeter C, Tienen TN, Hullegie W, der Sanden NV. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. Br J Sports Med 2016; 50:1506–1515.
21. Hamilton RT., Shultz SJ, Shmitz RJ. and Perrin DH. Triple hop distance as a valid predictor of lower limb strength and power. J Ath Train 2008; 43: 144– 151.
22. Noyes FR., Barber SD. and Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med 1991; 19: 513–518.
23. Nagai T, Schilaty ND, Laskowski ER, Hewett TE. Hop tests can result in higher limb symmetry index values than isokinetic strength and leg press tests in patients following ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2019 Apr 25.
24. Zwolski C, Shmitt LC, Thomas S, Hewett TE, Paterno MV. The Utility of Limb Symmetry Indices in Return-to-Sport Assessment in Patients With Bilateral Anterior Cruciate Ligament Reconstruction. Am J Sports Med. 2016 Aug; 44(8): 2030–8.
25. Roewer BD, Di Stasi SL, Snyder-Mackle L. Quadriceps strength and weight acceptance strategies continue to improve two years after anterior cruciate ligament reconstruction. J Biomech 2011. 44: 1948– 1953.
26. Wilk KE, Reinnold MM, Hooks TR. Recent advances in the rehabilitation of isolated and combined anterior cruciate ligament injuries. Ortop Clin North Am. 2003;l34:107–137.
27. Strandberg S, Lindström M, Wretling ML, Aspelin P and Shalabi A. Muscle morphometric effect of anterior cruciate ligament injury measured by computed tomography: aspects on using non-injured leg as control. BMC Musculoskelet Disord. 2013;14:150.
28. Holsgaard-Larsen A, Jense NH, Mortensen M, Aagaard P. Concurrent assessments of lower limb loading patterns, mechanical muscle strength and functional performance in ACL- patients – A cross-sectional study. The Knee. 2014;21: 66–73.
29. Rahnama N, Lees A, Bambaecichi E. A comparison of muscle strength and flexibility between the preferred and non-preferred leg in English soccer players. Ergonomics. 2005; 48:1568–1575.

30. Thorborg K, Couppe C, Petersen J, Magnusson SP, Holmich P. Eccentric hip adduction and abduction strength in elite soccer players and matched controls: a cross-sectional study. Br J Sports Med. 2011;45:10–13.
31. White K, Di Stasi SL, Smith AH, Snyder-Mackler L. Anterior cruciate ligament- specialized postoperative return-to-sports (ACL-SPORTS) training: a randomized control trial. BMC musculoskelet disord. 2013;14:108.
32. Clifford AM, Holder-Powell H. Postural control in healthy individuals. Clin Biomech 2010; 25:546–551.
33. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament deficient knees. Clin Orthop Relat Res. 1999;255:240–214.
34. Neeter C, Gustavsson A, Thomee P, Augustsson J, Thomee R,Karisson J. Development of a strength test battery for evaluating leg muscle power after anterior cruciate ligament injury and reconstruction. Knee Surg Sports Traumatol Arthrosc. 2006; 14:571–81.
35. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behav Res Methods. 2009 Nov;41(4):1149–60.
36. Brophy R, Silvers HJ, Gonzales T, Mandelbaum BR. Gender influences: the role of leg dominance in ACL injury among soccer players. Br J Sports Med. 2010;44: 694–697.
37. Harriss DJ, Atkinson G: Ethical standards in sport and exercise science research: 2014 update. Int J Sports Med. 2013; 34:1025–1028.
38. Bailey C. Force production symmetry during static, isometric, and dynamic tasks. Retrieved from ETSU electronic theses and dissertations 2014: http://dc.etsu.edu/etd/2388/ (2388).
39. Levine TR, Hullett CR. Eta squared, partial eta squared, and misreporting of effect size in communication research. Hum Com Res. 2002;28:612–625.
40. Logerstedt D, Lynch A, Michael AJ, Snyder-Mackler L. Symmetry restoration and functional recovery before and after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2013;21 859–868.
41. Ostenberg A, Roos E, Ekdhal C, Roos H. Isokinetic knee extensor strength and functional performance in healthy female soccer players. Scand J Med Sci Sports. 1988;8:257–264.
42. Davies WT, Myer GD, Read PJ. Is It time we better understood the tests we are using for return to sport decision making following acl reconstruction? A Critical Review of the Hop Tests. Sports Med. 2020; 50(3):485–495.
43. Holcomb WR, Rubley MD, Lee HJ, Guadagnoli MA. Effect of hamstring-emphasized resistance training on hamstring:quadriceps strength ratios. J Strength Cond Res. 2007;21:41–47.
44. Hartigan EH, Axe MJ, Snyder-Mackler L. Time Line for Noncopers to Pass Return-to-Sports Criteria After Anterior Cruciate Ligament Reconstruction. Orthop Sports Phys Ther. 2010; 40(3):141–154.
45. Thomee R, Neeter C, Gustavsson A, Thomee P, Augustsson J, Eriksson B, Karlsson J. Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2012; 20:1143–51.
46. Nawasreh Z, Logerstedt D, Cummer K, Axe M, Risberg MA, Snyder-Mackler L. Functional performance 6 months after ACL reconstruction can predict return to participation in same preinjury activity level 12 and 24 months after surgery. Br J Sports Med. 2018; 52:375–83.
47. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competition after anterior cruciate ligament reconstruction surgery: two thirds of patients have not returned by 12 months after surgery. Am J Sports Med. 2011;39:538.
48. Greenberg EM, Greenberg ET, Albaugh J, Storey E, Ganley TJ. Anterior Cruciate Ligament Reconstruction Rehabilitation Clinical Practice Patterns. A Survey of the PRiSM Society. The Orthop J Sports Med. 2019; 7(4), 2325967119839041. DOI: 0.1177/2325967119839041.
49. Gokeler A, Wellinga w, A. Benjaminsea C, Lemminka K, Seil R, Zaffagninie S. A critical analysis of limb symmetry indices of hop tests in athletes after anterior cruciate ligament reconstruction: A case control study. Orthop Traumatol Surg Res. 2017;103(6):947–951.
50. Kotsifaki A, Korakakis V, Whiteley R, Van Rossom S, Jonkers I. Measuring only hop distance during single leg hop testing is insufficient to detect deficits in knee function after ACL reconstruction: a systematic review and meta-analysis. Br J Sports Med. 2020; 54(3):139–153.
51. Bailey CA, Sato K, Burnett A, Stone MA. Force-production asymmetry in male and female athletes of differing strength levels. Int J Sports Physiol and Perf. 2015;10:504–508.
52. Bjordal JM, Arnoy F, Hannestad B, Strand T. Epidemiology of anterior cruciate ligament injuries in soccer. Am J Sports Med. 1997;25:341–345.
53. Flagg KY, Karavatas SG, Thompson SJr, Bennett C. Current criteria for return to play after anterior cruciate ligament reconstruction: an evidence-based literature review. Ann Transl Med. 2019;7(Suppl 7):S252.
54. Rein S, Fabian, T, Zwipp, H, Mittag-Bonsch M, Weindel F. Influence of age, body mass index and leg dominance on functional ankle stability. Foot Ankle Int. 2010;31:423–32.
55. Yanci J, Camara J. Bilateral and unilateral vertical ground reaction forces and leg asymmetries in soccer players. Biol Sport. 2016;33(2):179–83.
56. Kubo T, Muramatsu M, Hoshikawa Y, Kanehisa H. Profiles of trunk and thigh muscularity in youth and professional soccer players. J Strength Cond Res. 2010;24:1472–1479.
57. Sariyildiz M, Karacan I, Rezvani A, Ergin O, Cidem M. Cross-education of muscle strength: cross-training effects are not confined to untrained contralateral homologous muscle. Scand J Med Sci Sports. 2011; 21:359–64.