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Do ground reaction forces during unilateral and bilateral movements exhibit compensation strategies following ACL reconstruction?

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Abstract
Purpose The aims of the study were (1) to evaluate the leg asymmetry assessed with ground reaction forces (GRFs) during unilateral and bilateral movements of different knee loads in anterior cruciate ligament (ACL) reconstructed patients and (2) to investigate differences in leg asymmetry depending on the International Knee Documentation Committee Subjective Form (IKDC) in order to identify potential compensation strategies.
Methods The knee function of 50 ACL reconstructed (patella tendon) patients was examined at 31 ± 7 months after the surgery. GRFs were quantified during the sit-to-stand and stand-to-sit test, the step-up and step-down test, and the two- and one-leg vertical jump. Further, the IKDC score, the anterior–posterior knee laxity, and the concentric torque of the quadriceps and hamstring muscles were evaluated.
Results Differences between the operated and non-operated leg were found in the knee laxity, the quadriceps torque, and GRFs. The patients with low IKDC scores demonstrated greater leg asymmetries in GRFs compared to the patients with high IKDC scores.
Conclusions ACL reconstructed patients showed GRF asymmetries during unilateral and bilateral movements of different knee loads. Three compensation strategies were found in patients with low subjective knee function: (1) a reduced eccentric load, (2) an inter-limb compensation during bilateral movements, and (3) the avoidance of high vertical impact forces. These compensation strategies may be indicative of a protective adaptation to avoid excessive ACL strain. GRF measurements are practicable and efficient tools to identify individual compensation strategies during early rehabilitation.

Keywords Asymmetry · Biomechanics · IKDC · Knee joint · Jump test · Rehabilitation

Introduction

A rupture of the anterior cruciate ligament (ACL) is a devastating injury, and an ACL reconstruction is considered as the gold standard of care to return to the pre-injury activity level [24]. A return to unrestricted activities normally occurs 6–12 months after an ACL reconstruction surgery [20]. During rehabilitation, the knee function is usually evaluated with different subjective and objective tests such as questionnaires, laxity tests, and hop tests [20]. In this regard, it has been shown that 6–12 months after ACL reconstruction a low subjective knee function is indicative of lower symmetry indices in one-leg hop distance [29]. Interestingly, the restoration of symmetry in common clinical testing (e.g. one-leg jump height, knee flexion angle, and knee laxity) does not guarantee knee kinetic symmetry during the same or other movement tasks [13, 40]. Numerous studies have shown that patients who underwent an ACL reconstruction and returned to their pre-injury activity

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level still have knee momentum asymmetries during unilateral and bilateral multi-joint movement tasks [9, 16, 18, 33, 34, 40, 45, 46]. This is important because patients with greater asymmetries in biomechanical measures during landing and postural stability have a higher risk to sustain a second ACL injury [37]. Additionally, abnormal and asymmetric knee kinetics are related to poorer knee function after ACL reconstruction [3, 15, 17].

Commonly, inverse dynamic approaches with motion capture and ground reaction force (GRF) measurements are used to identify knee kinetic asymmetries in ACL reconstructed patients [18, 45, 46]. Based on joint momentum asymmetries during double-leg squats, Roos et al. [40] have identified two compensation strategies 2 years after an ACL reconstruction, which are combined in different proportions: (1) the transfer of support momentum to the non-operated leg and (2) the transfer of support momentum from the knee to the ankle and the hip of the operated leg. Since knee momentum asymmetries are correlated with asymmetries in peak GRF and impulse of vertical GRF, these measurements could be used as a practicable tool to identify asymmetries and possible compensation strategies during unilateral and bilateral movements of different knee loads after an ACL reconstruction throughout the rehabilitation efficiently [14]. In particular, in early stages of the rehabilitation, an evaluation of daily life activities such as sit-to-stand and stair-walking may be helpful to determine when patients can progress to more demanding tasks [29].

To the best of our knowledge, no study exists which has examined GRF asymmetries during both unilateral and bilateral movements of different knee loads in ACL reconstructed patients in relation to the subjective knee function. Such information may be clinically relevant as reference data and help to identify potential compensation strategies of ACL reconstructed patients with low subjective knee function. The aims of the present study were therefore (1) to evaluate the leg asymmetry assessed with GRFs during unilateral and bilateral movements of different knee loads and (2) to investigate differences in the leg asymmetry depending on the subjective knee function of ACL reconstructed patients. It was hypothesized that ACL reconstructed patients possess leg asymmetries in GRFs during unilateral and bilateral movements of different knee loads. Moreover, ACL reconstructed patients with lower subjective knee function may have higher asymmetries than patients with high subjective knee function.

Materials and methods

Fifty patients (16 females, 34 males; 29.2 ± 8.5 years, 1.76 ± 0.09 m, 82.4 ± 16.5 kg, BMI 26.7 ± 4.6 kg/m^2) with a primary unilateral ACL reconstruction were included

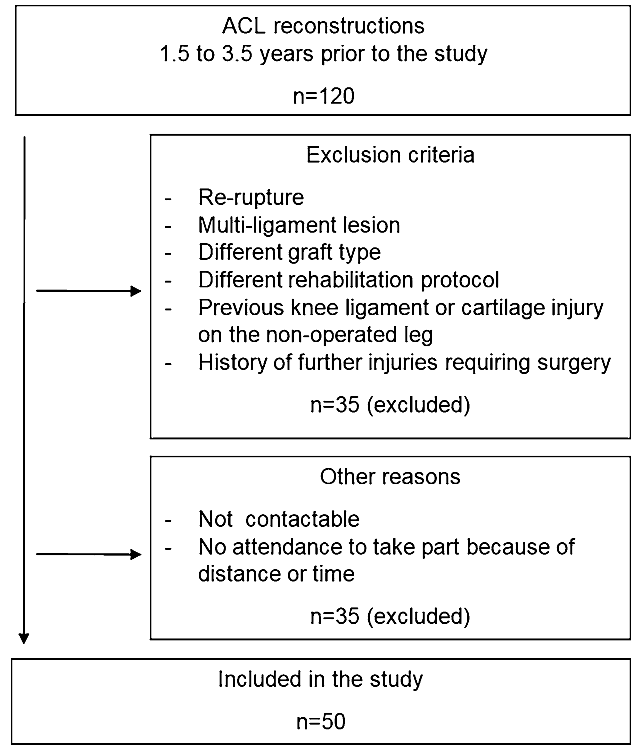

Fig. 1 Flow diagram of ACL reconstructed patients those who were excluded or included in the study

after applying the exclusion criteria (see Fig. 1). All surgeries were performed by the same team of physicians using a bone–patella tendon–bone autograft. At the time of surgery, 12 patients had a meniscus lesion, seven a cartilage defect, and 11 a combination of both. The patients were tested at 21–42 months (31 ± 7) postoperatively. Thirty-five of the 50 ACL reconstructions were performed on the dominant leg, which was defined as the leg used to jump preferentially. All patients were given written and oral information concerning the procedures and potential risks and gave their written informed consent according to the Declaration of Helsinki. The study was approved by the Ethical Review Board of the University of Witten/Herdecke.

Experimental design

The knee function of the ACL reconstructed patients was examined applying the following subjective and objective tests. The International Knee Documentation Committee 2000 Subjective Knee Form (IKDC) and the Lysholm Knee Questionnaire were used to evaluate the subjective knee function [2, 30]. The anterior–posterior knee laxity was measured in the operated and non-operated leg to quantify the knee stability. To examine leg asymmetries and possible compensation strategies, GRFs were quantified during unilateral and bilateral movements of different knee loads which included selected daily life activities and jumps. The tests were performed in the following order: sit-to-stand and stand-to-sit, step-up and step-down, two-leg vertical jump, and one-leg vertical jump. Finally, an isokinetic test was implemented to determine the concentric strength of the quadriceps and the hamstring muscles. If a test investigated one leg at one time, the non-operated leg was tested first.

Scores and anterior–posterior knee laxity

The IKDC questionnaire is a knee-specific measure of symptoms, function, and sports activity, resulting in a single index (0 = worst and 100 = optimal) [2]. For further statistical analysis, the IKDC score was converted into a standard score (z) as described in detail elsewhere, which permits a more valid comparison between patients who differ in terms of age and gender [2]. The Lysholm score estimates limp support, pain, swelling, instability, locking, stair-climbing, and squatting (0 = worst and 100 = optimal) [30]. Both scores have a test–retest reliability of ICC > 0.88 [12] and were imposed by one experienced physician. Anterior–posterior knee laxity was assessed with a knee arthrometer (Rolimeter, Aircast Europa, Neubeuern, Germany) in supine position with the tested knee flexed to 90°, as reported in detail elsewhere [39].

GRF tests

Sit-to-stand and stand-to-sit test

The patients were seated and instructed to take an upright stand followed by a seated position with a break of 2 s between both movements. The height of the seat was set at 39 cm which represents a deep mounted toilet. The movement was performed cross-armed for five times on two force plates (Kistler 9287BA). The seat was equipped with two additional force plates (Kistler 9286AA) to estimate the beginning and the end of the movement. Two 1-s intervals of the GRFs were analysed, if the vertical seat-force fell below 10 N (sit-to-stand) and until the vertical seat-force exceeded 10 N (stand-to-sit).

Step-up and step-down test

Starting from a standing position patients were instructed to step on a staircase, reach an upright standing position, and step-down after a 2-s break. The height was 39 cm which represents a bus exit. The patients could choose their preferred leg freely until one leg was chosen five times. Then, the contralateral leg was used until five trials of both legs were completed. The movement was performed cross-armed to avoid arm support on the knees. The GRFs were analysed using four force plates (Kistler 2× 9286AA and 2× 9287BA). The GRFs of the forward leg were analysed from the initial contact on the staircase to the staircase contact of the rear leg. The GRFs of the rear leg were analysed from the take-off of the forward leg to the take-off of the rear leg. The ground contact was defined when the vertical GRF first exceeded 10 N. The duration of each step-up and step-down was defined from the moment of take-off of the forward leg to the staircase contact of the rear leg.

Two-leg and one-leg vertical jump test

Ten two-leg jumps followed by three one-leg jumps were performed as vertical counter-movement jumps with arm swing and breaks of 30 s. For each leg, GRFs were analysed with a force plate (Kistler 9287BA) while jumping and landing applying a vertical force threshold of 10 N. The jump height was calculated using the impulse–momentum method, which is considered as the most accurate calculation method [28].

GRF analysis

The GRFs of up to four force plates (9286AA and 9287BA, Kistler Instruments AG, Winterthur, Switzerland) were sampled at 1000 Hz with a customized software (LabVIEW 2010, National Instruments, Austin, TX, USA). For all tests, the vertical GRF (vGRF) and the horizontal anterior–posterior GRF (hGRF) of the operated and the non-operated leg were analysed. The peak values of the vGRFs and/or the hGRFs were calculated for the sit-to-stand and stand-to-sit test, step-up and step-down test (forward and rear leg), as well as for the two-leg and the one-leg jump (jumping and landing). The impulses of the vGRFs were intended for sit-to-stand and stand-to-sit test, step-up and step-down test (forward and rear leg), as well as for the two-leg jump (jumping and landing) as the area under the vGRF–time curve (trapezoidal rule). Only in the two-leg jump (jumping and landing), the vGRFs of both legs were subtracted with half of the body weight before calculation of the impulse to assess the acceleration and deceleration as described elsewhere [5]. All kinetic parameters were normalized to the body weight, and the mean of all trials of each test was used for statistical analysis.

Isokinetic test

The torque of the quadriceps and hamstring muscles was measured at 60°/s using an isokinetic dynamometer (Cybex NORM, Humac, CA, USA). The patients were tested in a seated position with hip flexion of 100°. The range of motion was set at 0°–90° knee flexion, and a gravity compensation procedure was performed. After submaximal familiarization, five trials of maximal concentric knee extension and flexion were performed. To eliminate errors at the beginning and end of the trials, the mean peak torque of the second, third, and fourth trial was analysed and normalized to body weight. High reliability of ICC > 0.93 for this procedure has been reported in healthy and ACL reconstructed patients [7, 22].

Statistics

Because of the predominantly skewed distribution of the data, nonparametric tests were applied. First, the side-to-side differences between the operated and the non-operated leg were investigated with the Wilcoxon signed-rank Test. The influence of the lower limb dominance of the operated leg on the side-to-side differences between the operated and non-operated leg was analysed with the Mann–Whitney *U* Test. Then, the differences in the leg asymmetry depending on the subjective knee function were investigated. Therefore, the patients were separated in two same-sized groups depending on their IKDC (*z*) score. One group existed of the patients with an IKDC (*z*) score below zero and therefore lower than the mean of the patient's reference population values. Consequently, the other group included the same number of patients with the best IKDC (*z*) scores. The asymmetries were calculated as the difference between the non-operated and the operated leg divided by the maximum of the non-operated and the operated leg as reported previously [23]. The group differences were then analysed with the Mann–Whitney *U* Test. Effect sizes (*r*) were calculated by dividing the *z* value by the square root of *N* with 0.1 indicating a small, 0.3 a medium, and 0.5 a large effect [35]. The statistical significance was set at $P < 0.05$. The SPSS 22.0 software package for Windows (IBM, Armonk, USA) was used for all calculations.

Results

All patients were able to perform every test with the exception of one patient who did not dare performing the one-leg vertical jump. The mean IKDC score was 85.9 ± 11.7 (range 55.2–100), and Lysholm score 93.6 ± 7 (range 75–100). The mean IKDC (*z*) score was −0.038 ± 0.612 with a range of −1.54 to 0.76.

Operated versus non-operated leg

The anterior–posterior knee laxity was significantly higher in the operated compared to the non-operated knee (6.3 ± 2.0 vs. 4.5 ± 1.6 mm; $P < 0.001$, $r = 0.50$). The results of the GRF tests and the isokinetic test are summarized in Table 1. With the exception of the step-down test (rear leg) and the one-leg jump (jumping), side-to-side differences in the peak vGRF and the peak hGRF were found in all tests with the operated side being significantly lower ($P \leq 0.015$). During sit-to-stand, stand-to-sit, step-up (rear leg), step-down (rear leg) and the two-leg jump also significantly lower values existed in the vGRF impulse of the operated leg ($P \leq 0.026$). The duration of the step-up test was significantly shorter when patients performed the movement with the non-operated leg ($P \leq 0.017$). A significantly greater jump height was achieved for the non-operated leg in the one-leg jump ($P < 0.001$).

From the five trials in the step-up test, the patients started the test with the operated leg just as frequent as with the non-operated (median 2 vs. 3; n.s., $r = 0.01$). In the step-down test, the patients used the operated leg more often than the non-operated (median 4 vs. 1; $P = 0.035$, $r = 0.21$).

In the isokinetic test, significant torque differences were found between the operated and the non-operated leg for knee extension ($P = 0.006$, $r = 0.27$), but not for knee flexion (n.s., $r = 0.14$) (see Table 1).

The side-to-side differences of all assessed parameters between the operated and the non-operated leg are independent from leg dominance (n.s., $r < 0.27$).

High versus low IKDC group

The patients were separated in two groups using the IKDC (*z*) score (see Table 2). One group consisted of 20 patients with an IKDC (*z*) score below zero (low IKDC group). Consequently, the other group consisted of the 20 highest IKDC (*z*) scores (high IKDC group). Therefore, the high IKDC group had significantly greater IKDC, Lysholm, and IKDC (*z*) scores compared to the low IKDC group (all $P < 0.001$). A meniscus lesion, a cartilage defect, or a combination of both at the time of surgery was present in 7/2/2 patients in the high IKDC group and 3/3/9 patients in the low IKDC group, respectively. The sex, age, body mass index, and postoperative time of testing were comparable between the two groups. Also, the side-to-side difference of the anterior–posterior knee laxity as well as the bilateral and the unilateral jump height did not differ between the groups. The mean leg asymmetries of the GRFs and the isokinetic torque are shown in Table 3 for both groups separately. The low IKDC group had significantly higher side-to-side differences in the sit-to-stand test (peak vGRF), stand-to-sit test (peak vGRF; vGRF impulse), step-down test (forward leg: peak vGRF and hGRF; rear leg: vGRF impulse), two-leg vertical jump (jumping: vGRF impulse, peak hGRF; landing: peak vGRF), and one-leg vertical jump (landing: peak vGRF) ($P \leq 0.046$).

Discussion

The most important findings of the present study were that (1) patients at a mean of 31 months after ACL

Table 1 Kinetic parameters of the operated and the non-operated leg during the GRF tests and the isokinetic test (mean ± SD)

Test	Parameter		Direction	Operated leg	Non-operated leg	Difference (%)	P	r
Seat	Peak vGRF	N/BW_N	Sit-to-stand	0.609 ± 0.037	0.643 ± 0.052	5.2	0.001	0.32
			Stand-to-sit	0.570 ± 0.038	0.609 ± 0.055	6.5	0.002	0.32
	vGRF impulse	Ns/BW_N	Sit-to-stand	0.480 ± 0.032	0.500 ± 0.033	3.9	0.026	0.22
			Stand-to-sit	0.483 ± 0.028	0.502 ± 0.030	3.9	0.018	0.24
	Peak hGRF	N/BW_N	Sit-to-stand	0.058 ± 0.017	0.066 ± 0.016	12.0	0.002	0.31
			Stand-to-sit	0.046 ± 0.013	0.056 ± 0.016	19.2	<0.001	0.41
Staircase	Duration	s	Step-up	1.53 ± 0.20	1.49 ± 0.16	−2.7	0.017	0.24
			Step-down	1.29 ± 0.18	1.27 ± 0.17	−1.8	n.s.	0.14
	Forward leg							
	Peak vGRF	N/BW_N	Step-up	0.991 ± 0.037	1.013 ± 0.038	2.3	<0.001	0.46
			Step-down	1.783 ± 0.257	1.931 ± 0.323	7.7	<0.001	0.37
	vGRF impulse	Ns/BW_N	Step-up	0.647 ± 0.095	0.649 ± 0.082	0.4	n.s.	0.02
			Step-down	0.667 ± 0.088	0.679 ± 0.078	1.8	n.s.	0.09
	Peak hGRF	N/BW_N	Step-up	0.119 ± 0.021	0.128 ± 0.021	7.0	<0.001	0.38
			Step-down	0.278 ± 0.047	0.303 ± 0.065	8.0	0.003	0.29
	Rear leg							
	Peak vGRF	N/BW_N	Step-up	1.329 ± 0.110	1.421 ± 0.164	6.5	<0.001	0.46
			Step-down	1.016 ± 0.039	1.023 ± 0.032	0.6	n.s.	0.13
	vGRF impulse	Ns/BW_N	Step-up	0.829 ± 0.087	0.872 ± 0.116	4.9	0.001	0.34
			Step-down	0.581 ± 0.100	0.615 ± 0.103	5.6	<0.001	0.37
Two-leg vertical jump	Peak vGRF	N/BW_N	Jumping	1.104 ± 0.143	1.164 ± 0.151	5.1	<0.001	0.38
			Landing	2.286 ± 0.711	2.599 ± 0.726	12.0	<0.001	0.44
	vGRF impulse	Ns/BW_N	Jumping	0.108 ± 0.029	0.129 ± 0.034	16.4	0.007	0.27
			Landing	0.105 ± 0.021	0.132 ± 0.026	19.9	<0.001	0.47
	Peak hGRF	N/BW_N	Jumping	0.096 ± 0.027	0.106 ± 0.028	10.3	0.007	0.27
			Landing	0.358 ± 0.162	0.388 ± 0.186	7.6	0.015	0.24
One-leg vertical jump	Height	cm		12.6 ± 4.7	14.2 ± 4.9	11.5	<0.001	0.47
	Peak vGRF	N/BW_N	Jumping	1.883 ± 0.203	1.908 ± 0.234	1.3	n.s.	0.06
			Landing	3.209 ± 0.615	3.554 ± 0.699	9.7	<0.001	0.46
	Peak hGRF	N/BW_N	Jumping	0.163 ± 0.036	0.170 ± 0.038	3.9	n.s.	0.11
			Landing	0.275 ± 0.109	0.315 ± 0.132	12.5	0.001	0.33
Isokinetic	Torque	Nm/BW_N	Extension	0.200 ± 0.059	0.214 ± 0.058	6.4	0.006	0.27
			Flexion	0.117 ± 0.041	0.123 ± 0.039	5.3	n.s.	0.14

vGRF vertical ground reaction force, *hGRF* horizontal anterior–posterior ground reaction force, BW_N body weight in Newton

reconstruction exhibit leg asymmetries expressed by GRFs during unilateral and bilateral movements of different knee loads and (2) patients with low subjective knee function demonstrated greater leg asymmetries in GRFs compared to patients with high subjective knee function.

Operated versus non-operated leg

In light of the first main finding, the results revealed that side-to-side differences persist between the operated and the non-operated leg 31 months after ACL reconstruction. In anterior–posterior knee laxity, the side-to-side difference of 1.8 mm is lower than 3 mm and therefore non-pathological [7]. The mean side-to-side difference in maximal knee extension torque of 6.4 % is lower than 10.9 % [10] and 10 % [31] reported 3.2 and 5.8 years after ACL reconstruction with a patellar tendon autograft, respectively. However, no side-to-side differences were found for the maximal knee flexion torque which is in line with other studies [31]. Importantly, leg asymmetries in GRFs were present during the sit-to-stand and stand-to-sit test, step-up and step-down test, two-leg vertical jump, and one-leg vertical jump. These observations show that the patients have reduced the GRFs of the operated leg during these movements. Other authors have also shown asymmetries in GRF during sit-to-stand and drop

Table 2 The anthropometric characteristics, the side-to-side differences of the anterior–posterior knee laxity, the subjective ratings, and the jump performance of the high and the low IKDC group (mean ± SD)

Parameter	High IKDC group	Low IKDC group	*P*	*r*
Sex (*n*)	9 f, 11 m	3 f, 17 m	n.s.	0.32
Age (years)	29.0 ± 7.4	31.8 ± 10.2	n.s.	0.11
BMI (kg/m^2)	26.7 ± 4.0	27.8 ± 5.1	n.s.	0.12
Postoperative (month)	31.8 ± 6.9	30.9 ± 6.7	n.s.	0.06
Laxity difference OL–NOL (mm)	2.2 ± 2.0	1.8 ± 1.7	n.s.	0.07
IKDC (*z*) score	0.76 ± 0.46	−0.65 ± 0.52	<0.001	0.86
IKDC score [0–100]	94.8 ± 3.4	74.6 ± 10.4	<0.001	0.85
Lysholm score [0–100]	98.3 ± 3.4	88.2 ± 7.0	<0.001	0.73
Two-leg jump height (cm)	27.2 ± 8.7	28.4 ± 8.7	n.s.	0.08
One-leg jump height				
OL (cm)	11.9 ± 4.7	12.3 ± 5.1	n.s.	0.03
NOL (cm)	13.6 ± 5.1	14.4 ± 5.4	n.s.	0.08

OL operated leg, *NOL* non-operated leg

jumps in ACL reconstructed patients 2 months and up to 2 years after surgery, respectively [27, 36]. In the current study, most of the revealed mean differences between the operated and the non-operated leg are lower than 10–15 %, which has been considered to be an abnormal asymmetry [43]. However, 49 of 50 patients have a side-to-side difference >15 % in, at least, one kinetic parameter.

While possible mechanistic explanations are beyond the scope of the current study, they should be mentioned for the readers briefly. The leg asymmetries may be a reasonable adaptation based on the individual requirements (e.g. mechanical and/or physiological) and movement experience of the patients during and after rehabilitation. An altered sensorimotor control may be an explanation of the leg asymmetries, which might be permanent after ACL reconstruction [19]. In this context, the neuromuscular characteristics of the operated leg are different from that of the non-operated leg 6–9 months after ACL surgery [8]. Additionally, Baumeister et al. [4] have shown that cortical activation patterns during force and position reproduction tests differ between controls and ACL reconstructed patients with a patellar tendon autograft. With this in mind, it is questionable that the targets of rehabilitation programs are often geared towards healthy individuals and not towards ACL reconstructed patients with high subjective and objective knee function.

To the best of our knowledge, this study is the first to show that ACL reconstructed patients use their operated leg preferably to step-down from a 39 cm staircase. This unique finding may be important in context of activities performed during daily life. This mismatch may result from the avoidance of high eccentric loads in the rear leg during step-down and could lead to long-term adaptations of the musculoskeletal unit. In this context, a study has shown that patients have a decreased knee-specific physical activity level 20 years after an ACL injury while showing a similar general level of physical activity as controls [42]. The authors concluded that the patients perform well in some activities, but have an inferior performance in more knee-demanding tasks and therefore choose activities that possess less loading on the knee joint. Consequently, it should be reasonable during rehabilitation to find out whether ACL reconstructed patients choose their non-operated leg preferably to perform unilateral movement tasks.

A further finding is that the magnitude of the assessed side-to-side differences is independent of the leg dominance. Considering that healthy individuals also show no important kinetic differences between the dominant leg and the non-dominant leg during one-leg jumps, it is reasonable that the non-operated leg of ACL reconstructed patients can be used as a reference in the examined movement tasks irrespective of leg dominance [44].

High versus low IKDC group

The second main finding revealed that the low IKDC group demonstrated greater GRFs asymmetries compared to the high IKDC group even if both groups have similar anthropometrics, side-to-side differences in anterior–posterior knee laxity, and jump performance. Since there are no jump performance differences between the low and the high IKDC group, clinicians should be aware that the same performance does not necessarily be indicative of similar subjective knee function and symmetric biomechanics [33]. The low IKDC group showed greater leg asymmetries in GRFs as follows:

1. In the stand-to-sit test (vGRF impulse) and the step-down test (rear leg: vGRF impulse), the low IKDC group has higher side-to-side differences than the high IKDC group. These results indicate a reduced load of the operated leg during a unilateral and a bilat-

Table 3 Leg asymmetries (%) of the kinetic parameters during the GRF tests and the isokinetic test of the high and the low IKDC group (mean ± SD)

Test	Parameter	Direction	High IKDC group	Low IKDC group	*P*	*r*
Seat	Peak vGRF	Sit-to-stand	1.5 ± 8.7	9.1 ± 10.5	0.020	0.37
		Stand-to-sit	3.4 ± 11.2	11.2 ± 10.8	0.040	0.32
	vGRF impulse	Sit-to-stand	1.5 ± 10.7	8.0 ± 12.0	n.s.	0.22
		Stand-to-sit	1.2 ± 10.7	9.2 ± 9.4	0.026	0.35
	Peak hGRF	Sit-to-stand	10.0 ± 22.8	12.1 ± 24.5	n.s.	0.01
		Stand-to-sit	15.6 ± 26.8	19.4 ± 23.6	n.s.	0.05
Staircase	Duration	Step-up	0.3 ± 8.7	4.6 ± 7.9	n.s.	0.21
		Step-down	0.3 ± 7.6	3.5 ± 8.8	n.s.	0.15
	Forward leg					
	Peak vGRF	Step-up	1.8 ± 1.9	2.5 ± 3.7	n.s.	0.08
		Step-down	3.6 ± 11.7	13.0 ± 9.8	0.011	0.40
	vGRF impulse	Step-up	1.6 ± 5.5	−0.2 ± 9.9	n.s.	0.13
		Step-down	0.3 ± 10.2	3.1 ± 10.3	n.s.	0.14
	Peak hGRF	Step-up	6.4 ± 9.5	7.3 ± 9.8	n.s.	0.07
		Step-down	3.8 ± 12.8	12.4 ± 13.5	0.028	0.34
	Rear leg					
	Peak vGRF	Step-up	6.3 ± 7.2	6.3 ± 8.5	n.s.	0.05
		Step-down	0.0 ± 3.4	0.5 ± 2.9	n.s.	0.09
	vGRF impulse	Step-up	2.1 ± 6.8	6.7 ± 9.0	n.s.	0.24
		Step-down	1.6 ± 9.6	9.2 ± 8.8	0.035	0.33
Two-leg vertical jump	Peak vGRF	Jumping	3.2 ± 8.2	7.8 ± 8.0	n.s.	0.30
		Landing	7.9 ± 13.3	16.8 ± 14.1	0.046	0.32
	vGRF impulse	Jumping	1.3 ± 35.4	33.3 ± 23.4	0.003	0.46
		Landing	14.5 ± 19.9	25.0 ± 21.8	n.s.	0.27
	Peak hGRF	Jumping	−0.3 ± 15.3	14.7 ± 20.3	0.017	0.37
		Landing	4.0 ± 17.4	3.8 ± 15.9	n.s.	0.02
One-leg vertical jump	Height		12.0 ± 14.6	13.5 ± 18.4	n.s.	0.03
	Peak vGRF	Jumping	0.7 ± 5.2	1.8 ± 7.5	n.s.	0.01
		Landing	5.5 ± 9.8	12.5 ± 10.8	0.019	0.37
	Peak hGRF	Jumping	4.1 ± 14.4	3.8 ± 19.3	n.s.	0.01
		Landing	4.6 ± 24.4	15.3 ± 19.0	n.s.	0.23
Isokinetic	Torque	Extension	6.4 ± 10.3	11.4 ± 22.0	n.s.	0.06
		Flexion	0.6 ± 17.5	11.0 ± 22.1	n.s.	0.25

vGRF vertical ground reaction force, *hGRF* horizontal anterior–posterior ground reaction force

eral movement with submaximal eccentric strength. Lower maximal eccentric quadriceps peak torque in the operated leg of 7.8 % was reported even 3.2 years after ACL reconstruction with patellar tendon autograft [10]. These side-to-side differences could be important since a low eccentric quadriceps torque may cause a tibial translation that reaches the limit of the passive knee joint displacement [26]. Another study revealed a negative relationship between the functional level using the Modified Cincinnati Scale and the asymmetry in eccentric quadriceps peak torque in ACL reconstructed patients 20.2 months after surgery [47].

2. The low IKDC group has higher side-to-side differences in the sit-to-stand test (peak vGRF) and the two-leg vertical jump (jumping: peak hGRF, vGRF impulse) than the high IKDC group. Furthermore, in the stand-to-sit (vGRF impulse) and the two-leg vertical jump (peak vGRF) exist high but non-significant group differences with medium effect sizes. This fact may indicate that bilateral movements were more suited to reveal possible asymmetries in GRFs, because the patients could spread the load between the legs and use inter-limb compensation strategies, primarily. Inter-limb compensation was also described using knee kinetics during the double-leg squats with symmetric peak knee flexion angles [40]. During unilateral movements of the same load, patients may use inter-joint compensations [14, 32], which are not be represented in GRF asymmetries.

3. In the step-down test (forward leg: peak vGRF), the two-leg vertical jump (landing: peak vGRF), and the one-leg vertical jump (landing: peak vGRF), the patients with lower subjective knee function avoid high impact forces in the operated leg compared to the non-operated leg. The dominant mechanism of ACL injuries has been discussed widely in the past [1, 6]. Beside the theory of quadriceps dominance and related anterior shear forces, the posterior tibial slope and the compounded high axial compressive forces on the tibiofemoral joint could also cause anterior translation of the tibia. The maximum force transferred to the knee would be at the peak vertical GRF, which is greatest in the extended knee landing condition [1, 38]. High compressive forces result from inadequate absorption of GRFs by the lower leg and simultaneous contraction of quadriceps and hamstring muscles [6]. Interestingly, most of the ACL injuries occurred during landing in or near full knee extension and a planted foot [1, 25]. During step-up, step-down, lunge, and one-legged sit-to-stand, the ACL strain also increases as the knee is extended [21].

Based on these observations, it can be concluded that patients with low subjective knee function may demonstrate three compensation strategies compared to patients with high subjective knee function which are (1) a reduced eccentric load, (2) an inter-limb compensation during bilateral movements, and (3) the avoidance of high vertical impact forces. These compensation strategies may be an indication of a protective central nervous adaptation to avoid excessive ACL strain in the reconstructed knee. The fact that these compensation strategies were shown during activities of daily life could be important in early stages of rehabilitation. Despite the potential presence of compensation strategies, the two IKDC groups showed no asymmetry differences in maximum isokinetic torque during knee extension and flexion. However, the torque asymmetries in the low IKDC group are, by the trend, greater. Bryant et al. [8] have shown that ACL reconstructed patients with higher knee functionality demonstrated a higher motor unit recruitment reflective of less M. vastus lateralis and medialis type II muscle fibre atrophy, a better quadriceps strength, and an increase in musculotendinous stiffness of the lower limb musculature. Such adaptations may result from long-term persisting compensation strategies.

After surgery, an unconscious self-organization of the sensorimotor system of the patients may occur. The rehabilitation has to procure normal range of motion and positive experience in various repetitive movements [41]. In all phases during rehabilitation, pain is inversely associated with knee function [11]. If the knee joint works well, positive structural adaptations (e.g. muscle hypertrophy) will occur and compensation strategies may change or disappear. Otherwise, a compensation strategy may facilitate to perform the movement task or patients avoid such movements. Therefore, the revealed leg asymmetries and compensation strategies may be meaningful for each patient. Future studies should investigate whether more individualized rehabilitation programs, which procure positive experience in various repetitive movements, are able to reduce leg asymmetries and compensation strategies in ACL reconstructed patients.

The GRFs are not equivalent to the knee kinetic load, which is frequently presented as knee momentum and increased with greater knee flexion, e.g. during landing [38]. For example, in ACL reconstructed patients, the operated leg has a decreased knee flexion during a one-leg jump (jumping and landing) compared to the non-operated leg [18, 33]. Therefore, the decrease in knee flexion in the operated leg could contribute to an increase in the knee momentum asymmetry, which may be underestimated by the single observation of the GRF asymmetry. However, the use of GRF analyses may be clinically relevant to examine unilateral and bilateral movement tasks during rehabilitation. From a practical point of view, the GRF measurements are useful tools to identify individual compensation strategies in daily rehabilitation procedures and help to determine when patients can progress to more demanding tasks.

Conclusions

ACL reconstructed patients showed GRF asymmetries during unilateral and bilateral movements of different knee loads. Three compensation strategies were found in patients with low subjective knee function: (1) a reduced eccentric load, (2) an inter-limb compensation during bilateral movements, and (3) the avoidance of high vertical impact forces. These compensation strategies may be indicative of a protective adaptation to avoid excessive ACL strain in the reconstructed knee. Patients with a low subjective functionality may use these compensation strategies to perform unilateral and bilateral movements of different knee load. The GRF measurements are practicable and efficient tools to identify individual compensation strategies early during rehabilitation. It is imperative that clinicians incorporate this knowledge and transfer it into clinically feasible tests.

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