Phase-Specific Ground Reaction Force Analyses of Bilateral and Unilateral Jumps in Patients With ACL Reconstruction

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Background: In patients who have undergone anterior cruciate ligament (ACL) reconstruction, there is a weak correlation between subjective evaluation of knee function on questionnaires and clinical or biomechanical test results.

Hypothesis: Patients with lower subjective knee function will demonstrate lower ground-reaction forces (GRFs) in the operated leg and greater GRF asymmetries in both phase-specific and functional data analysis (FDA) approaches compared with patients with higher subjective knee function.

Study Design: Descriptive laboratory study.

Methods: The GRFs of the operated and nonoperated legs of 40 patients who previously underwent ACL reconstruction (patellar tendon) were analyzed during unilateral and bilateral countermovement jumps at a mean 2.5 years after surgery. The patients were separated into 2 groups depending on their International Knee Documentation Committee (IKDC) Subjective Form score: low IKDC and high IKDC.

Results: Both phase-specific and FDA approaches showed lower GRF values in the operated compared with the nonoperated leg within the low-IKDC group during bilateral jumps. Moreover, lower GRF values were also present in the operated and nonoperated legs in the low-IKDC group compared with those of the high-IKDC group. Differences in GRFs were predominantly observed during the eccentric deceleration phase of jumping.

Conclusion: Patients with previous ACL reconstruction who have limited subjective knee function have lower GRF values and greater GRF asymmetries, suggesting the use of interlimb compensation strategies.

Clinical Relevance: The study results lead to a better understanding of the motor control needed during the eccentric and concentric movement phases of unilateral and bilateral jumps in patients who have undergone ACL reconstruction.

Keywords: functional data analysis; asymmetry; eccentric; concentric

The rupture of the anterior cruciate ligament (ACL) is a significant knee injury.[18,30] In the normal and sport populations, the injury incidence is 0.03% to 0.04% and 0.15% to 3.67% per year, respectively.[30] Surgical reconstruction is the gold standard of care to return to the preinjury activity level.[23] Usually, return to sport can occur 6 to 12 months postsurgery.[18]

Different subjective and functional tests to evaluate knee function during and after the rehabilitation process have been developed. While questionnaires as well as hop and/or jump tests are useful in the clinical setting, more complex kinetic, kinematic, and neuromuscular measurements are used in scientific studies.[18,26] However, the relationship between the subjective evaluation of knee function by the patients and clinical or biomechanical tests is weak overall.[10,31,32,41] Previous studies have shown that patients still exhibit leg asymmetries during unilateral and bilateral movements, despite returning to their preinjury activity level.[7,13,16,32,37,45,46] Moreover, these leg asymmetries have not correlated with clinical scores and test results.[5,10,47] Consequently, it is worth investigating what factors distinguish patients with low versus high subjective knee function results.

The majority of biomechanical studies on knee function after ACL reconstruction have used conventional data-analysis approaches, reducing continuous data into discrete parameters (eg, peak or mean angle, force, and torque

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values) and potentially leading to a loss of information during specific movement phases.[19,22,36] A recent study has shown that ACL-reconstructed patients with low subjective knee function reduce the load of the operated leg during eccentric quadriceps activities of daily living.[5] Therefore, it is important to investigate specific movement phases in these patients.

With that in mind, one study has used a phase-specific approach, allowing a distinction between eccentric and concentric movement phases via ground reaction forces (GRFs) measured during bilateral vertical jumps.[22] The findings showed that greater asymmetries were evident in the concentric phase in ACL-reconstructed elite ski racers after their return to sport compared with healthy controls.[22] Another study revealed differences in the duration of the propulsive phase during bilateral vertical drop jumps in ACL-reconstructed female handball players 6 years postsurgery.[43]

A further promising approach to analyze continuous data of movements, including both eccentric and concentric phases, is functional data analysis (FDA), which considers the time-dependent structure of a signal.[34,44] Typically, an FDA transforms raw data into functions, which can then be registered to reduce phase variability while preserving the signal's shape and amplitude.[9,34] In a recent study that applied an FDA approach to the kinematic data of unilateral jumps, functional knee-joint abnormalities were found in ACL-deficient patients more than 20 years after injury.[19]

Taken together, the few studies that have applied phase-specific and FDA approaches to analyze vertical jumps indicate that these approaches can provide additional insights into the motor control of ACL-reconstructed patients. However, no previous study has investigated whether differences in GRFs would be seen between patients with high and low subjective knee functional outcomes. Such knowledge may be helpful to identify compensation strategies in ACL-reconstructed patients, potentially supporting rehabilitation processes. Therefore, the aim of this study was to investigate differences in GRFs during unilateral and bilateral vertical jumps in ACL-reconstructed patients with different subjective knee function scores by using the phase-specific and FDA approaches. We hypothesized that ACL-reconstructed patients with lower subjective knee function would exhibit lower GRFs in the operated leg and higher GRFs asymmetries than patients with high subjective knee function.

METHODS

This study used a data set from a previous study that investigated GRF asymmetries in ACL-reconstructed patients during movements of different knee loads using discrete parameters.[5] Specifically, phase-specific and FDA approaches were applied to the vertical GRFs of unilateral and bilateral jumps.

Participants

From a total of 50 patients, 40 patients with a primary unilateral ACL reconstruction (bone–patellar tendon–bone autograft) were clustered into 2 same-sized groups according to their subjective knee function using the International Knee Documentation Committee (IKDC) 2000 Subjective Knee Form, as described below.[5] The anthropometric characteristics of both groups are listed in Table 1. At the time of surgery, a meniscus lesion, a cartilage defect, or a combination of both was evident in 7/2/2 and 3/3/9 patients within the high- and low-IKDC groups, respectively. The study was preapproved by the ethical review board of the University of Wuppertal, and all patients provided written informed consent according to the Declaration of Helsinki.

TABLE 1
Anthropometric Characteristics, IKDC (z) Scores, and Jump Heights of the High- and Low-IKDC Groups[a]

Parameter	High-IKDC Group	Low-IKDC Group	P	d
Sex, n				
Female	9	3		
Male	11	17		
Age, y	29 ± 7	32 ± 10	.325	0.32
BMI, kg/m^2	27 ± 4	28 ± 5	.412	0.27
Postoperative, mo	32 ± 7	31 ± 7	.678	0.14
IKDC (z) score	0.46 ± 0.14	−0.65 ± 0.52	<.001[b]	3.01
Bilateral jump height, cm	27.2 ± 8.7	28.4 ± 8.7	.657	0.15
Unilateral jump height, cm				
OP	12.1 ± 4.8	12.3 ± 5.0	.902	0.04
nOP	13.6 ± 5.2	14.5 ± 5.4	.594	0.18

[a]Results are shown as mean ± SD unless otherwise indicated. BMI, body mass index; IKDC, International Knee Documentation Committee; nOP, nonoperated leg; OP, operated leg.
[b]$P < .05$.

Subjective Knee Function

Subjective knee function was evaluated using the IKDC score, which ranges from 0 (worst) to 100 (best).[1] Then, the IKDC score was converted into a standard score (z), which permits a more valid comparison among patients who differ regarding their age and sex.[1] The low-IKDC group consisted of all patients (n = 20) with an IKDC (z) score less than zero, indicating a subjective knee function lower than the mean for that patient's reference population. The high-IKDC group included the same number of patients with the best IKDC (z) scores.[5]

Vertical Jump Tests

All patients performed 10 bilateral followed by 3 unilateral countermovement jumps. In the unilateral jumps, the nonoperated leg was always tested first. One patient from the low-IKDC group did not perform the unilateral jump because of a fear of reinjury. All jumps were performed with an arm swing and a rest period of 30 seconds between the jumps. For each leg, the vertical GRFs were sampled at 1000 Hz using 2 force plates (Typ 9287BA, Kistler Instruments AG) and customized software (LabVIEW 2010,

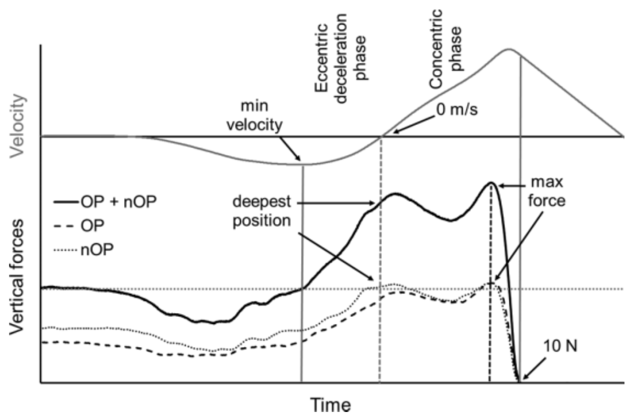

Figure 1. Exemplary phase definition using the ground reaction force (GRF) and calculated center-of-mass velocity during the bilateral jump. The eccentric deceleration phase was defined from the maximum negative to zero velocity (ie, the deepest position) followed by the concentric phase until the GRF reached a threshold of <10 N. Discrete time points of the GRFs were calculated at the end of the eccentric phase and the maximum resultant GRF (OP + nOP). OP, operated leg; nOP, nonoperated leg.

National Instruments). The jump heights were calculated using the impulse-momentum method applying a vertical force threshold of 10 N.[28]

Phase-Specific Analysis

The velocity of the center of mass was obtained by the time integration of the acceleration signal, which was calculated from the total vertical GRF of a jump. Then, the eccentric deceleration phase was defined from the maximum negative to zero velocity.[22] Subsequently, the concentric phase followed until the total vertical GRF reached a threshold of <10 N (Figure 1). The kinetic impulses of the right and left limb were calculated by the time integration of the force-time signal over the appropriate periods[22] and expressed as percentages of the sum of both phases during each jump. Additionally, discrete time points of the vertical GRFs were calculated and normalized to body weight at the maximum resultant force and end of the eccentric phase. Moreover, the duration of the eccentric deceleration phase was determined as a percentage of the duration of both phases. The mean values were used for statistical analyses.

Functional Data Analysis

The FDA was performed for each leg during the unilateral and bilateral jumps as well as for both groups to identify differences in vertical GRFs. Therefore, the GRFs of both legs were time-normalized to 0% to 100% from the beginning of the eccentric deceleration to the end of the concentric phase with steps of 0.5% using linear interpolation. Functional data objects were generated using a fourth-order B-spline technique with 201 knots, which is typically used to represent noncyclical, nonperiodic data.[44] The fit of the GRFs by the functional data objects was visually checked. A landmark registration procedure was performed to ensure that the end of the eccentric phase was always at the same position.[34] Thereafter, for each patient, the mean curves of all trials were calculated. Finally, functional permutation *t* tests for the 2 groups were used to detect differences within and between the functional data objects of both IKDC groups.[6]

Statistical Analysis

The normal distribution of the data was tested using the Kolmogorov-Smirnov test with no need for further transformations. A side (operated vs nonoperated leg) × group (high vs low IKDC) mixed-model analysis of variance (ANOVA) was used to assess potential effects within the unilateral jump heights and discrete GRF parameters. Partial eta squared effect sizes (η_P^2) were calculated, with thresholds for small, medium, and large effects being set at 0.01, 0.06, and 0.14, respectively.[8] Additionally, differences between the groups as well as between the operated and nonoperated leg were analyzed by independent and dependent *t* tests, respectively. For the interpretation of the meaningfulness, effect sizes according to Cohen's *d* were calculated, with thresholds for small, medium, and large effects being set at 0.20, 0.50, and 0.80, respectively.[8] The SPSS 22.0 software package (IBM Corporation) was used for the descriptive and *t*-test calculations. The statistical significance level was set at $P < .05$. All FDA computations were performed with R 3.1.2[33] using the R-package "fda."[35]

RESULTS

The high- and low-IKDC groups were similar with regard to sex, age, body mass index, time from ACL reconstruction, and jump height. As expected, the high-IKDC group has significantly higher IKDC (*z*) scores (Table 1). While the mixed-model ANOVA showed no interaction effect (side × group) for unilateral jump height, $F(1, 37) = 0.88$; $P = .355$; $\eta_P^2 = 0.02$, there was a main effect for side, $F(1, 37) = 22.68$; $P < .001$; $\eta_P^2 = 0.38$, but not for group, $F(1, 37) = 0.12$; $P = .730$; $\eta_P^2 < 0.01$. Within both IKDC groups, the unilateral jump height of the operated leg was lower than that of the nonoperated leg, with small effect sizes (high-IKDC group, $P = .006$, $d = 0.23$; low-IKDC group, $P = .002$, $d = 0.43$).

Phase-Specific Analysis

The mixed-model ANOVA revealed interaction effects (side × group) for relative force at the deepest point, eccentric impulse, and concentric impulse during the bilateral jump as well as for relative force at the deepest point during the unilateral jump (Table 2). Isolated main effects were found in the maximum relative force during the bilateral jump (side) and eccentric impulse during the unilateral jump (group). The descriptive and *t*-test statistics of the GRF parameters for both groups are shown in Table 3.

Operated Versus Nonoperated Leg (Within-Group Comparisons). In the low-IKDC group, the operated leg

TABLE 2
Results of the Side (OP vs nOP) by Group (High vs Low IKDC) Mixed-Model Analysis of Variance[a]

	Side (OP vs nOP)			Group (High vs Low IKDC)			Side × Group		
	F(1, 37)	P	η^2_P	F(1, 37)	P	η^2_P	F(1, 37)	P	η^2_P
Bilateral jump									
Maximum relative force, % BW	17.23	<.001[b]	0.31	0.35	.558	0.01	3.06	.088	0.07
Relative force (deepest point), % BW	11.81	.001[b]	0.24	2.18	.148	0.05	6.29	.017[b]	0.14
Eccentric impulse, %	9.08	.005[b]	0.19	1.96	.170	0.05	7.17	.011[b]	0.16
Concentric impulse, %	25.62	<.001[b]	0.40	1.95	.170	0.05	5.71	.022[b]	0.13
Unilateral jump									
Maximum relative force, % BW	0.73	.400	0.02	2.09	.157	0.05	0.41	.527	0.01
Relative force (deepest point), % BW	1.57	.219	0.04	13.27	.001[b]	0.26	4.65	.038[b]	0.11
Eccentric impulse, %	0.40	.533	0.01	4.78	.035[b]	0.11	0.54	.468	0.01
Duration eccentric phase, %	1.81	.187	0.05	2.48	.124	0.06	0.18	.674	<0.01

[a]BW, body weight; IKDC, International Knee Documentation Committee; nOP, nonoperated leg; OP, operated leg.
[b]$P < .05$.

TABLE 3
Ground Reaction Force Parameters of the High- and Low-IKDC Groups and the Results of the Within- and Between-Group Comparisons (t Tests)[a]

	High-IKDC Group				Low-IKDC Group				Between Groups			
									OP vs OP		nOP vs nOP	
	OP	nOP	P	d	OP	nOP	P	d	P	d	P	d
Bilateral jump												
Maximum relative force, % BW	1.11 ± 0.13	1.15 ± 0.12	.103	0.32	1.06 ± 0.15	1.16 ± 0.19	.001[b]	0.57	.230	0.40	.966	0.01
Relative force (deepest point), % BW	1.03 ± 0.15	1.05 ± 0.17	.571	0.12	0.91 ± 0.13	1.03 ± 0.16	<.001[b]	0.88	.013[b]	0.85	.820	0.07
Eccentric impulse, %	14.6 ± 3.8	15.0 ± 5.4	.824	0.09	10.4 ± 4.2	17.0 ± 4.1	<.001[b]	1.64	.002[b]	1.07	.184	0.44
Concentric impulse, %	33.8 ± 4.3	36.6 ± 3.5	.051	0.73	32.4 ± 4.1	40.2 ± 4.3	<.001[b]	1.88	.294	0.35	.007[b]	0.93
Unilateral jump												
Maximum relative force, % BW	1.94 ± 0.2	1.95 ± 0.25	.871	0.02	1.83 ± 0.19	1.86 ± 0.24	.343	0.15	.085	0.58	.291	0.35
Relative force (deepest point), % BW	1.72 ± 0.25	1.71 ± 0.28	.574	0.07	1.43 ± 0.15	1.50 ± 0.19	.011[b]	0.43	<.001[b]	1.47	.012[b]	0.87
Eccentric impulse, %	27.4 ± 7.9	26.6 ± 6.9	.286	0.12	22.4 ± 5.9	22.4 ± 6.4	.949	0.01	.031[b]	0.74	.059	0.64
Duration eccentric phase, %	33.2 ± 4.8	35.1 ± 5.7	.182	0.37	36.0 ± 6.0	37.0 ± 6.3	.560	0.16	.116	0.53	.333	0.32

[a]Results are shown as mean ± SD. BW, body weight; IKDC, International Knee Documentation Committee; nOP, nonoperated leg; OP, operated leg.
[b]$P < .05$.

showed lower values in maximum relative force, relative force at the deepest point, eccentric impulse, and concentric impulse compared with the nonoperated leg during the bilateral jump. Additionally, the relative force at the deepest point of the operated leg was lower during the unilateral jump. No further differences within both IKDC groups were evident (Table 3).

High- Versus Low-IKDC Group (Between-Group Comparisons). The operated leg of the low-IKDC group showed lower values in the relative force at the deepest point and eccentric impulse compared with those of the high-IKDC group during the bilateral and unilateral jumps. Furthermore, the nonoperated leg in the low-IKDC group exhibited higher values for concentric impulse and relative force at the deepest point during the bilateral and unilateral jumps, respectively. No further differences between both IKDC groups were found (Table 3). Between both groups, the relative duration of the eccentric deceleration phase also did not differ during the bilateral jump (high-IKDC group, 38.2% ± 4.4%; low-IKDC group, 40.2% ± 4.2%; $P = .167$, $d = 0.46$).

Functional Data Analysis

For the FDA, a total of 780 and 213 GRF curves were analyzed for the bilateral and unilateral jumps, respectively. The outputs of the FDA are shown in Figures 2 and 3, presenting the mean relative GRFs, P values of each permutation t test, pointwise values of the t statistic, and pointwise critical values. Differences between 2 curves

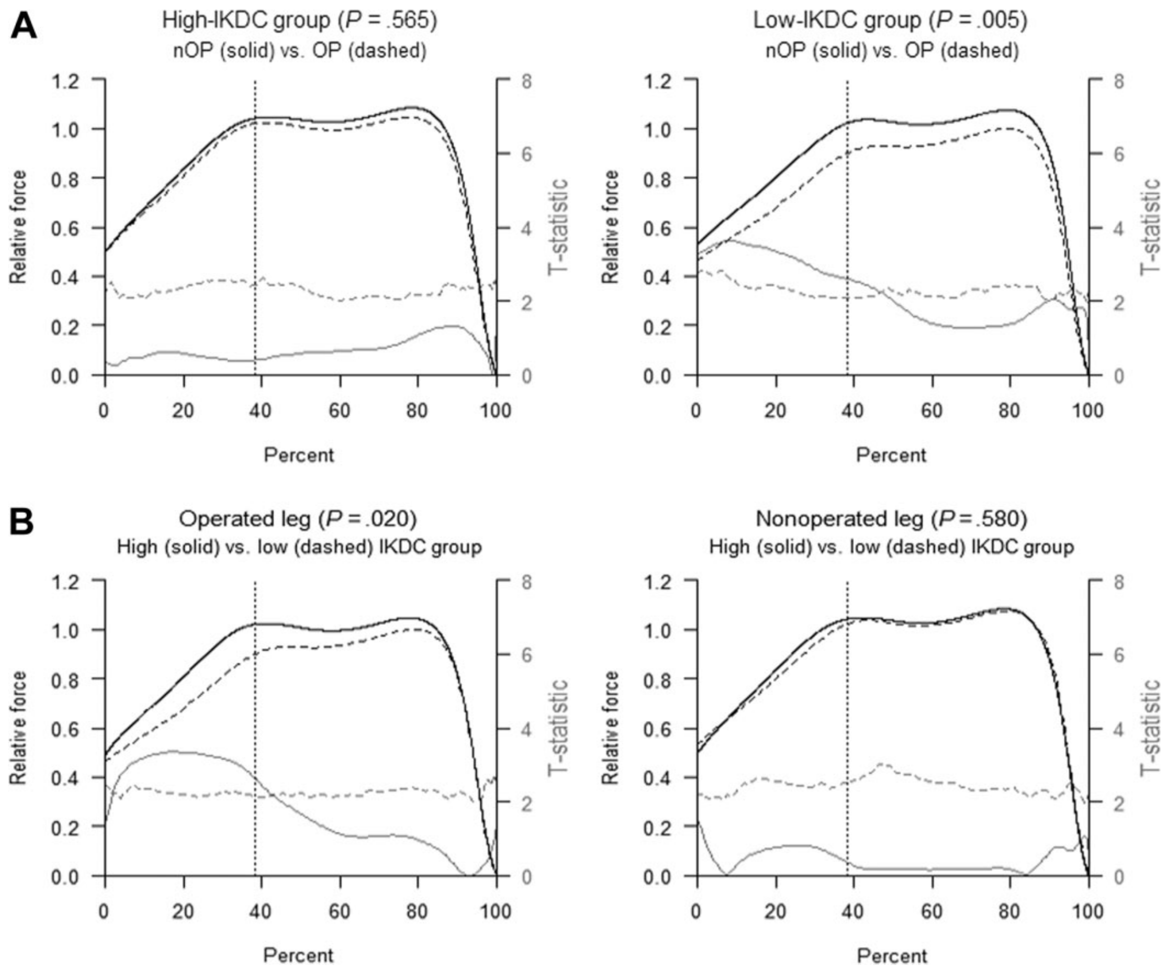

Figure 2. Functional data analysis outputs of the bilateral jumps from the (A) within-group and (B) between-group comparisons. Each graph includes the mean relative ground reaction forces (black lines), end of the eccentric phase (vertical line), *P* value of the permutation *t* test, pointwise values of the *t* statistic (solid gray line), and the pointwise critical values (dashed gray line). IKDC, International Knee Documentation Committee; OP, operated leg; nOP, nonoperated leg.

were present if the pointwise value of the *t* statistic was greater than the pointwise critical value.

Operated Versus Nonoperated Leg (Within-Group Comparisons). In the low-IKDC group, differences between the GRFs of the operated and nonoperated leg were found during the bilateral jump. These differences predominantly occurred in the eccentric deceleration phase of the jump (0%-50%), where the GRF of the operated leg was lower than that of the nonoperated leg. No further GRF differences were present within both IKDC groups in the bilateral and unilateral jump.

High Versus Low-IKDC Group (Between-Group Comparisons). The operated leg of the low-IKDC group showed lower GRFs than that of the high-IKDC group in the eccentric deceleration phase of the bilateral (0%-40%) and unilateral jump (0%-60%). Moreover, the nonoperated leg of the low-IKDC group had lower values than the nonoperated leg of the high-IKDC group during the eccentric deceleration phase (0%-40%) in the unilateral jump.

DISCUSSION

This study is the first to apply phase-specific and FDA approaches to GRFs of bilateral and unilateral jumps in ACL-reconstructed patients with different subjective knee function outcomes. The major findings were that the use of these approaches revealed GRF differences (1) between the operated and nonoperated leg for patients with low subjective knee function but not for patients with high subjective knee function and (2) within the operated and nonoperated legs between patients with low and high subjective knee function, which were predominantly present in the eccentric deceleration phase of the jumps.

The first main finding was that within the low-IKDC group, all the calculated GRF parameters of the bilateral jump were lower in the operated leg than those in the nonoperated leg. Moreover, the FDA revealed lower GRFs for the operated leg during the bilateral jump. Previous studies have shown that ACL-reconstructed patients use intralimb[37,38] or interlimb[37,38,40] compensation strategies during

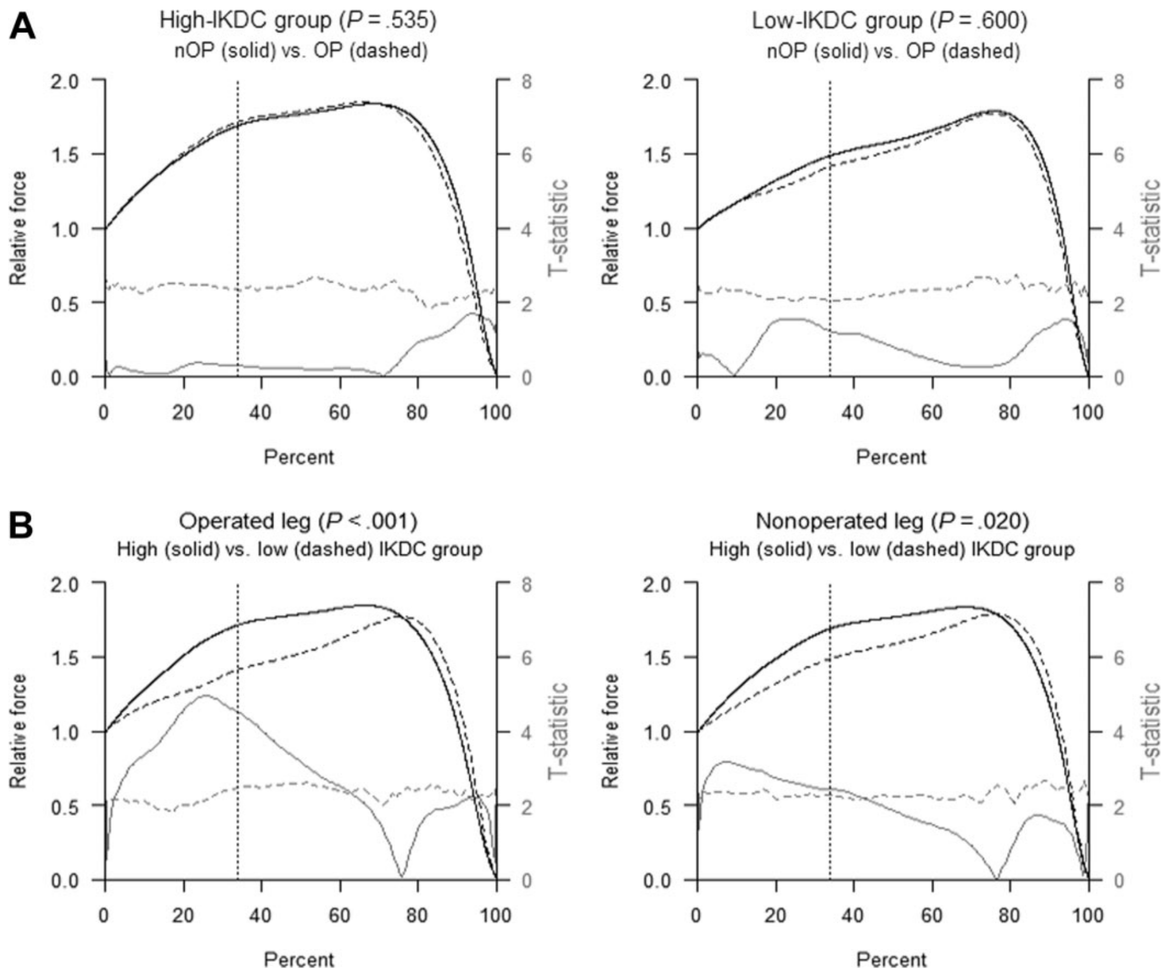

Figure 3. Functional data analysis outputs of the unilateral jumps from the (A) within-group and (B) between-group comparisons. Each graph includes the mean relative ground reaction forces (black lines), end of the eccentric phase (vertical line), *P* value of the permutation *t* test, pointwise values of the *t* statistic (solid gray line), and the pointwise critical values (dashed gray line). IKDC, International Knee Documentation Committee; OP, operated leg; nOP, nonoperated leg.

bilateral movements to achieve their movement target. The GRF differences we observed in patients with low IKDC scores suggest that they use interlimb compensation strategies during bilateral jumps. Based on the results of the FDA, the interlimb compensation strategies were predominantly present during the eccentric deceleration phase of the bilateral jump. Using GRFs, large differences were also found between the operated and nonoperated limb during the descent phase (0%-20%) of a squat.[40] During gait, ACL-reconstructed patients with weak quadriceps strength show deviations during weight acceptance, when an eccentric quadriceps contraction is required to control knee flexion and shock absorption.[27] Moreover, one study revealed eccentric weakness in the quadriceps of the injured leg during isokinetic testing, which was inversely correlated to the functional level of ACL-reconstructed patients.[48] After their return to sport, ACL-reconstructed ski racers showed no differences in the asymmetry of the eccentric phase during bilateral jumps compared with uninjured skiers, while differences were found in the concentric phase.[22] Interestingly, the athlete with the highest asymmetry in the eccentric deceleration phase (20.5%) experienced a medial collateral ligament injury to the contralateral limb after data collection.[22] A symmetric eccentric movement phase may be important for the return-to-sport decision. Therefore, rehabilitation after an ACL reconstruction should focus on eccentric knee movements, especially in patients with low subjective knee scores.

In contrast to the first main finding, within the high-IKDC group no differences between the operated and nonoperated leg were found during the bilateral and unilateral jump for both the phase-specific and FDA approaches. Generally, high IKDC scores are associated with more quadriceps strength and symmetry, the ability to meet return-to-sport criteria, and successful return to preactivity levels.[49] These results collectively suggest that our patients with high subjective knee function were well rehabilitated. Moreover, the patients in the high-IKDC group achieved only a slightly higher vertical jump height during the unilateral jump when using their nonoperated leg (1.5 cm). This difference is lower than previously reported in ACL-reconstructed patients 6 months postsurgery (4.2 cm).[17]

Interestingly, the patients in the high-IKDC group did not have a significantly higher vertical jump height than those in the low-IKDC group.

The second main finding of this study was that the phase-specific and FDA approaches identified differences within the operated and nonoperated legs between patients with low and high subjective knee function. The relative force at the deepest point during the unilateral jump was lower in the nonoperated leg of the low-IKDC group compared with that of the high-IKDC group, while the maximum relative force and jump height were similar. Moreover, in the unilateral jumps, the FDA showed that the GRFs of the nonoperated leg were lower in the low-IKDC group compared with that in the high-IKDC group during the eccentric deceleration phase. Another study found no differences in the maximum isokinetic quadriceps strength of the nonoperated legs between high- and low-IKDC groups.[49] However, it has been shown that explosive quadriceps activation properties in the nonoperated leg in ACL-reconstructed patients were lower than those of the controls, while maximum strength properties were similar.[29] These results point out that submaximal quadriceps strength properties of the nonoperated leg may be altered after ACL reconstruction, even if maximal properties are not. Therefore, both maximal and submaximal properties should be assessed, and consequently addressed in training and therapy. As ACL-reconstructed patients have a high risk of sustaining a second ACL tear, even in the contralateral leg,[39] future research should investigate whether such adaptations in patients with low subjective knee function predisposes them to further injuries. During both the bilateral and unilateral jumps, the relative force at the deepest point and the eccentric impulse of the operated leg were lower in the low-IKDC group compared with the high-IKDC group. Furthermore, the FDA revealed lower GRFs in the operated leg of the low-IKDC group during the first part of the bilateral (0%-40%) and unilateral (0%-60%) jump. Thus, the GRF differences between the operated legs of the low- and high-IKDC groups were also predominantly present during the eccentric movement phase. A reduced knee load during eccentric movement phases may underpin their importance for evaluating knee function, as eccentric movements can lead to a high strain of the ACL, which was shown for simulated eccentric squats and downhill running.[3,20] Moreover, already low eccentric quadriceps torque can cause a tibial translation that reaches the limit of the passive knee joint displacement.[24] Whether the observed differences in the eccentric phase of the jumps were based on adapted movement coordination and/or muscle properties remains unclear and needs further research. The role of eccentric strength in return-to-sport decisions is unclear.[2] While no isolated parameter (eg, hop length, jump height) can predict the risk of a (re)injury,[4] eccentric movement and strength properties should be considered to evaluate postoperative knee function.[25] Therefore, phase-specific analyses of movements could be useful during the rehabilitation process to identify compensation strategies and to determine when patients can progress to more demanding tasks.

In this study, no differences in the relative phase duration between and within the groups were found. Compared with controls, female and male handball players with a previous ACL reconstruction also showed no differences in timing parameters during unilateral countermovement jumps.[42,43] Therefore, the analysis of phase durations in ACL-reconstructed patients during countermovement jumps can be negligible. However, this result may be important for the FDA approach, wherein the general timing information of the GRFs is ignored.

Overall, the relative force at the deepest point during both bilateral and unilateral jumps seems to represent eccentric force properties and corresponds with the overall result of the FDA. Therefore, this parameter, which is easy to calculate, may be useful to evaluate knee function in ACL-reconstructed patients using GRFs of bilateral and unilateral jumps. The use of FDA may help discriminate between 2 or more groups of patients, when peak or average values reveal no differences,[15] potentially leading to a better understanding of motor control in ACL-reconstructed patients. Moreover, phase-specific analyses in vertical jump tests may give more detailed information in the evaluation of strength asymmetries[21] and potential injury risk factors in healthy athletes.

Limitations

This study is based on a macroscopic approach to analyze different phases of vertical jumps. As the detailed muscle actions during the jumps are unknown, the terms *eccentric* and *concentric* are incorrect. However, throughout the literature, the descent of the center of mass during vertical jumps is referred to as the eccentric phase, while the concentric phase describes the ascent of the center of mass.[12] Additionally, this study used GRFs of bilateral and unilateral vertical jumps to evaluate potential differences between patients of different subjective knee function. Because intralimb movement strategies are not detectable by the single use of GRFs, a symmetric test result may be an indication of adequate compensation by the hip and ankle musculature and may not necessarily indicate normal knee extension force.[14,37] However, asymmetries in GRF parameters correlate with knee momentum asymmetries during athletic tasks and, therefore, could be helpful to identify possible movement strategies.[11] Furthermore, this study is limited to ACL-reconstructed patients with a bone–patellar tendon–bone autograft. Patients with other graft types may show different results.

CONCLUSION

The use of phase-specific and FDA approaches in unilateral and bilateral jumps revealed GRF differences between the operated and nonoperated leg within patients with low subjective knee function. Moreover, GRF differences were present within the operated and nonoperated legs between patients with low and high subjective knee function. The revealed GRF differences were predominantly present in the eccentric deceleration phase of the jumps.

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