

Article

Between-Limb Symmetry during Double-Leg Vertical Hop Landing in Males an Average of Two Years after ACL Reconstruction is Highly Correlated with Postoperative Physiotherapy Supervision Duration

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Abstract: This study investigates whether double-leg and single-leg vertical hops (VH) landing between-limb symmetry in males, an average of two years after anterior cruciate ligament (ACL) reconstruction (ACLR), is associated with postoperative physiotherapy supervision duration. Thirty-eight healthy controls and thirty-eight males after primary unilateral ACLR, with the use of ipsilateral semitendinosus and gracilis tendon autograft, on average two years before, underwent bilateral peak vertical ground reaction force (vGRF) measurements during double-leg and single-leg VH landing, using two force plates. The vGRF was normalized to the body mass (vGRF BM). The vGRF BM limb symmetry index (LSI) was calculated. Tests for dependent and independent samples and linear Pearson's correlation coefficient (r) calculations were performed. There were significant between-leg differences in the double-leg ($p < 0.001$) vGRF BM values. The longer the postoperative physiotherapy supervision duration was, the higher the double-leg VH LSI values ($r = 0.727$; $p < 0.001$). There was also a significant but weak positive association between the single-leg VH landing LSI value and the physiotherapy supervision duration ($r = 0.333$; $p = 0.041$). Between-limb symmetry during double-leg VH landing in males, an average of two years after ACLR, was correlated with postoperative physiotherapy supervision duration. Fully supervised postoperative physiotherapy for a minimum of six months is more effective for improving VH landing limb symmetry in patients after ACLR.

Keywords: anterior cruciate ligament reconstruction; physical therapy specialty; rehabilitation

1. Introduction

The anterior cruciate ligament (ACL) is the most frequently injured of all knee ligaments, with an incidence of 0.7 to 2.5 tears per 1000 athletic exposures in young and athletically active people [1]. The arthroscopic reconstruction of the ruptured ligament (ACLR) remains a gold standard of treatment, especially for patients with functional knee instability, as well as for those wishing to return to cutting and pivoting sports [2]. In the literature, there are a large number of standardized postoperative protocols after ACLR; however, there is still no consensus regarding postoperative physiotherapeutic procedure without the direct supervision of a physiotherapist; this procedure is called unsupervised or partially supervised physiotherapy [3–6]. Since the 1990s, there has been a general assumption that unsupervised physiotherapy after ACLR produces results equal to those obtained with supervised physiotherapy [7–10]; however, the assumption has been changing [11,12].

The vertical hop is a multi-joint movement task that is commonly used in the clinical environment, and is considered an important dynamic movement in physical activity [13,14]. The current literature highlights the landing strategies analysis during standardized jump tasks as an interesting assessment tool, and several studies have reported an asymmetric landing pattern among patients after ACLR [15–17]. One of the qualitative methods for evaluating the lower limbs loading symmetry during landing is the measurement of the vertical compound of the ground reaction forces (vGRF) [18,19]. The measurements are taken with the use of force plates and are useful for assessing some aspects of dynamic muscle function in clinical settings. This approach is commonly called jumping mechanography [20,21]. The assessment of the symmetry of the lower limbs in ACL-reconstructed patients is commonly based on the analysis of the percentage difference between the lower limbs or on the basis of the so-called limb symmetry index (LSI). The value of the LSI is being used as one of the criteria for returning to sport activity after ACLR [22,23]. An abnormal lower limb symmetry in ACL-reconstructed patients, which is characterized by asymmetries between the right and left legs, is defined by a between-limb percentage difference greater than 10% or an LSI lower than 90 [23,24]. However, some authors suggest using diverse thresholds for different performance tasks [22]. In this context, it seems critical to establish the normative percentage difference and LSI values obtained by healthy individuals for the movement of the task being assessed. What is more, given that bilateral deficits are present after ACLR [25], which may result in a falsely high limb symmetry [26], the symmetry should be analyzed with caution, and the absolute values should be compared to the norm from the matched healthy controls.

Short-term post-ACL reconstruction alterations in limb symmetry during double-leg vertical jump landing, dependent on postoperative physiotherapy supervision duration, have been reported [27]. The issue seems clinically important, as the altered loading of the knee joint may trigger the development of osteoarthritis, and therefore influence quality of life [13,28]. Some studies have also suggested that abnormalities in the knee function during dynamic movements may increase the risk of subsequent ipsilateral and contralateral ACL injuries [29–31]. Nonetheless, it is hard to find any studies evaluating the influence of postoperative physiotherapy supervision on the vertical jump landing between-limb symmetry in a longer follow-up.

This study investigated whether double-leg and single-leg vertical hop landing between-limb symmetry in males, an average of two years after ACLR, is associated with the duration of postoperative physiotherapy supervision.

2. Materials and Methods

The experiment was approved by the ethics committee in 2006 and was conducted according to the ethics guidelines and principles of the Declaration of Helsinki. All of the participants who participated in the study were informed of the purpose and approach to be used, and signed an informed consent form to participate in the study. The study was conducted in an academic center in 2006–2018. The study had a retrospective cohort study design.

2.1. Participants

The initial sample consisted of 280 patients who started the postoperative physiotherapeutic procedure after ACLR in the physiotherapy center where the study was conducted between 2006 and 2017.

Based on the medical documentation of the patients gathered in the physiotherapy center where the study was conducted, we telephonically invited 120 male patients at least one year after primary unilateral ACLR with the use of autologous ipsilateral semitendinosus and gracilis muscles tendons graft, to participate in the examination. All of the selected patients were well trained and frequently sporting pre-ACL injury. The algorithm for selecting patients for the examined group is presented in the flowchart of the study (Figure 1). Therefore, 38 ACL-reconstructed patients were included in the final study sample. Additionally, a control group including 38 healthy, well-trained, and frequently

sporting males, matched in terms of gender, age, body mass, and body height, were selected from the volunteers. The characteristics of the studied participants are presented in Table 1.

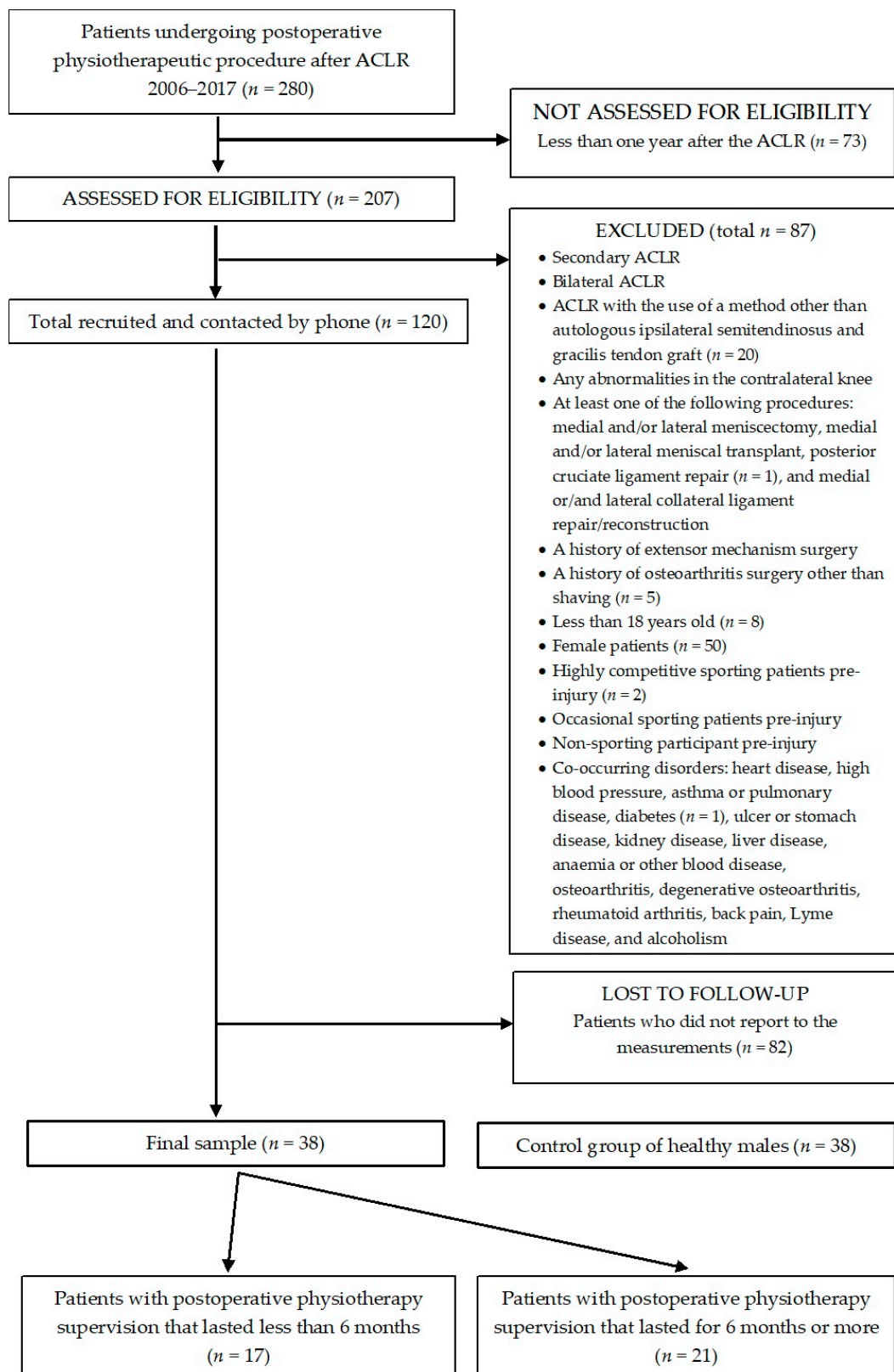


Figure 1. Flowchart of the study; ACLR: anterior cruciate ligament reconstruction; *n*, number of individuals.

Table 1. Characteristics of studied participants; ACL: anterior cruciate ligament; ACLR: anterior cruciate ligament reconstruction; *n*: number of individuals; n/a: not applicable; *p*: level of statistical significance of the difference between patients with postoperative physiotherapy supervision < 6 months and patients with postoperative physiotherapy supervision ≥ 6 months, and control group; vGRF BM: vertical ground reaction force normalized to body mass. Values are expressed as the arithmetic mean and 95% confidence interval.

Studied Feature	ACL-Reconstructed Patients			Control Group (<i>n</i> = 38)	<i>p</i>
	Total Number of ACL-Reconstructed Patients (<i>n</i> = 38)	Physiotherapy Supervision < 6 Months (<i>n</i> = 17)	Physiotherapy Supervision ≥ 6 Months (<i>n</i> = 21)		
Age (years)	29.71 (26.98, 32.44)	30.24 (27.13, 33.34)	29.29 (24.78, 33.79)	26.16 (24.87, 27.45)	0.061
Body mass (kg)	79.95 (76.41, 83.48)	81.06 (74.52, 87.60)	79.05 (74.91, 83.18)	78.84 (75.89, 81.80)	0.735
Body high (cm)	179.95 (177.97, 182.12)	178.24 (175.04, 181.43)	181.33 (178.25, 184.42)	182.82 (180.66, 184.97)	0.062
Time between injury and ACLR (days)	32.42 (13.86, 50.98)	34.12 (2.89, 71.13)	31.05 (12.00, 50.09)	n/a	0.870
Physiotherapy supervision (weeks)	23.32 (19.94, 26.69)	15.35 (12.58, 18.13)	29.76 (25.85, 33.68)	n/a	<0.001
Follow-up (weeks)	103.18 (90.14, 116.23)	113.59 (92.41, 134.76)	94.76 (77.78, 111.75)	n/a	0.148

2.2. Surgical Procedure

The mean time between ACL injury and reconstruction was 32 days (Table 1). The studied patients underwent post-traumatic primary unilateral one-incision arthroscopically assisted ACLR, with the use of autologous ipsilateral double-strand semitendinosus–double-strand gracilis graft. The reconstructions were performed by the same two senior surgeons. The transtibial technique was utilized. The tourniquet use was the same in all of the patients. Femoral nerve blocks were not used. Thirty patients underwent single-bundle ACLR, and eight patients underwent double-bundle ACLR.

2.3. Postoperative Physiotherapeutic Procedure

All of the supervised physiotherapy sessions were held at the physiotherapy center, where the study was conducted under the strict supervision of a physiotherapist. The physiotherapy was performed by a team of two physiotherapists with more than 10 years of apprenticeship, in the center where the study was conducted with patients with musculoskeletal disorders, especially with ACL-reconstructed patients who followed the procedure described by Czamara (2008) [32] in the same physiotherapy center. The patients went through one-on-one physiotherapy sessions. The physiotherapeutic procedure included the following four consecutive stages: stage I, from the day of surgery to the fifth week after surgery (frequency of visits was four to five times a week); stage II, from the sixth to the twelfth week after the surgery (frequency of visits was four times a week); stage III, from thirteenth week to the nineteenth week after the surgery (frequency of visits was four times a week); and stage IV, from the twentieth week to six to nine months after surgery (frequency of visits was three times a week) [32]. A single physiotherapeutic session lasted on average two hours. The supervised physiotherapy sessions were regularly monitored [33].

The studied sample of patients included patients who completed an average of 23.32 ± 10.26 weeks of supervised physiotherapy (Table 1). However, for more detailed data analysis purposes, the ACL-reconstructed patients ($n = 38$) were retrospectively divided into patients with postoperative physiotherapy supervision that lasted less than six months ($n = 17$; 15.35 ± 5.40 weeks), and patients with postoperative physiotherapy supervision that lasted for six months or more ($n = 21$; 29.76 ± 8.60 weeks) (Table 1). The patients with a postoperative physiotherapy supervision duration less than six months informed us that, based on reasons independent of their orthopedic surgeons and physiotherapists, they had refused to continue the supervised physiotherapy. They had been informed about the main goals of the remaining physiotherapeutic stages, and independently returned to structured gym exercises and activity.

In the group of patients with postoperative physiotherapy supervision that lasted less than six months, there were 70% ($n = 12$) who received the operation on the dominant leg. In the group of patients with postoperative physiotherapy supervision that lasted for six months or more, the dominant limb was operated on in 67% of the patients ($n = 14$). The dominant leg was defined as the preferred leg for kicking a ball.

2.4. Test Protocol

Prior to the vertical ground reaction force (vGRF) measurements during double-leg and single-leg hops, a history was taken, and all of the studied participants underwent an examination involving a bilateral manual Lachman test and pivot shift test, performed in all of the studied participants by the same orthopedic surgeon. The body height and mass were measured.

The measurement of vGRF during the double-leg and single-leg vertical hops was performed consecutively by using the MTD-balance system (MTD Systems, Neunburg v. Wald, Germany), containing two force plates for right and left legs separately. The method of vGRF measurement using the MTD-balance system was based on the study by Czamara (2011) [18]. The procedure was very similar to that of Veilleux and Rauch (2010), and Matheson et al. (2013) [20,21]. All of the vGRF measurements in the study were performed by one well-experienced examiner.

The intra-rater and inter-rater test–retest reliability of the test protocol using the MTD-balance system was presented in our previous study, and indicated an excellent intra-rater reliability for double-leg vertical hop landing (ICC = 0.84–0.96) and single-leg vertical hop landing (ICC = 0.95–0.96). The inter-rater reliability was considered good for double-leg vertical hop landing (ICC = 0.67–0.69), and excellent for single-leg vertical hop landing (ICC = 0.94–0.95) [27]. We also performed vGRF measurements using the presented protocol in clinical practice as one of the functional benchmarks to examine patients after ACLR undergoing physical therapy in our physiotherapy center [33].

The participants were asked to abstain from unaccustomed strenuous exercise for at least 24 h before the measurements, and to avoid eating a heavy breakfast in the morning before the measurements and within two hours of the test. They were dressed in a comfortable sport outfit and sport shoes.

The measurements were preceded by a warm-up on a cycloergometer. The participants were instructed by the examiner on the technique of double-leg and single-leg vertical hops. Each participant performed a few trials. The examiner used verbal “start” and “stop” commands to start and end the participant’s continuous hopping. Each vertical hop was performed in the upright position. The protocol did not allow for countermovement, and arm movement during the hops was restricted.

The force plates were adjusted to indicate a mass of 0 kg before a participant stepped onto it. At first, the vGRF values during double-leg vertical hops were measured. At the beginning of the measurement, the examined participant placed his right foot on the middle of the right force plate and left foot on the middle of the left plate (Figure 2a). Then, he performed 10 continuous double-leg vertical hops (Figure 2b). Next, the vGRF values during the single-leg vertical hops were measured, starting with the uninvolved leg in ACL-reconstructed patients and with the dominant limb in the control group. The examined participant placed the foot of the studied leg in the middle of the force plate (Figure 3a) and performed 10 continuous single-leg vertical hops (Figure 3b). The contralateral leg was flexed 90° at the knee joint. Measurement was then performed for the contralateral leg in the same way [18,27].

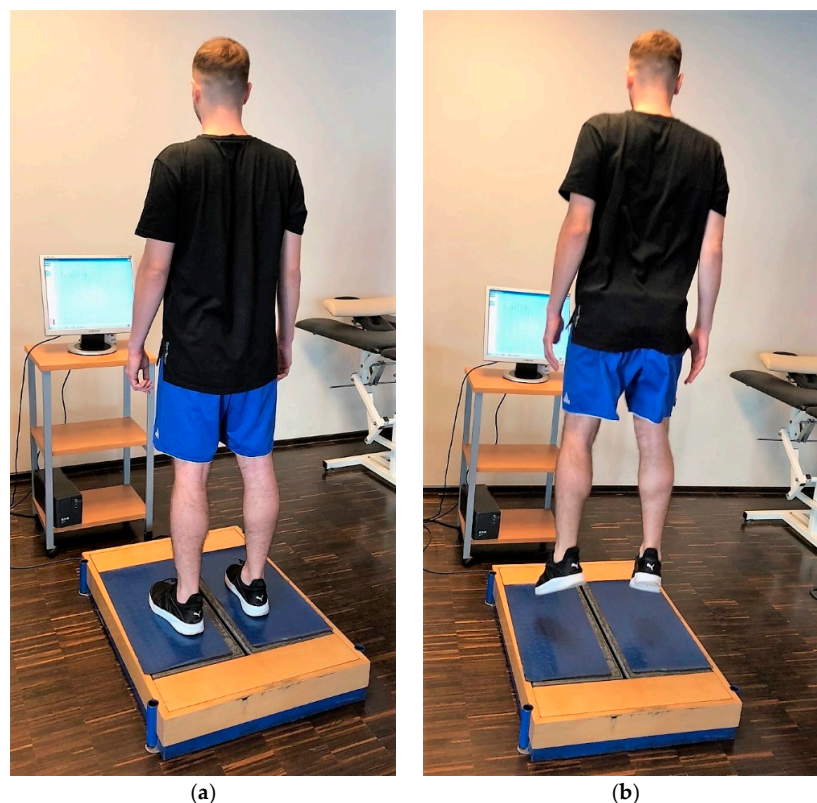


Figure 2. (a) The starting position for the vertical ground reaction force (vGRF) measurements during double-leg vertical hops; (b) the double-leg vertical hop.



Figure 3. (a) The starting position for the vertical ground reaction force (vGRF) measurements during single-leg vertical hops; (b) the single-leg vertical hop.

2.5. Data Analysis

The peak vGRF (N) during the double-leg and single-leg vertical hop landing was analyzed. The arithmetic mean of the obtained peak landing vGRF of all of the executed two-legged (Figure 4) and one-legged (Figure 5) vertical hops was calculated separately for each leg. Then, the obtained vGRF values were normalized to body mass (kg), yielding vGRF BM ($\text{N} \cdot \text{kg}^{-1}$).

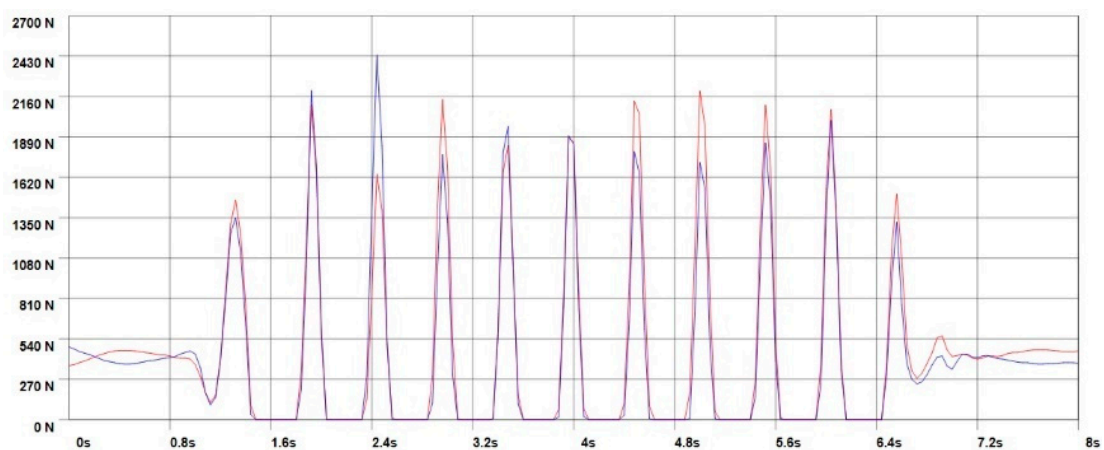


Figure 4. An example of 10 consecutive double-leg vertical hops vGRF values obtained in the right (blue line) and left (red line) legs, with the highest vGRF values representing the peak landing values. The first double-leg landing was registered at 2.0 s.

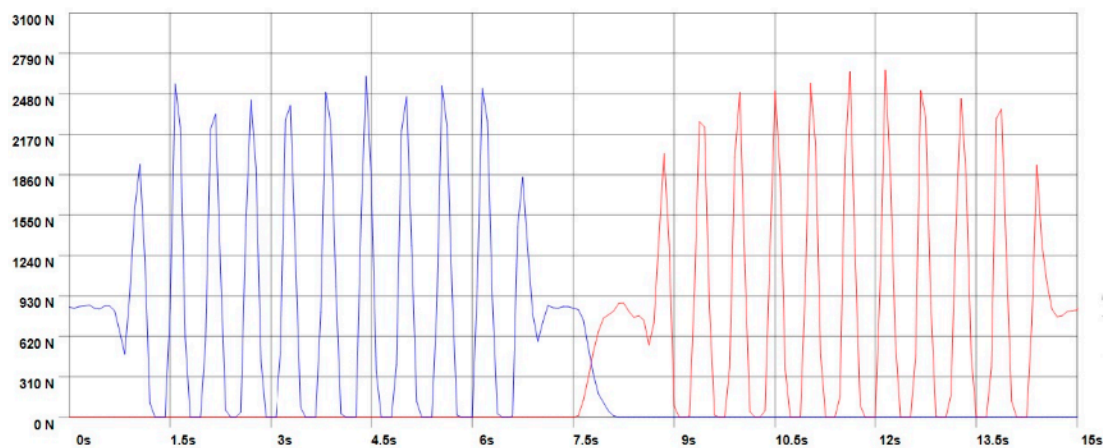


Figure 5. An example of 10 consecutive single-leg vertical hops vGRF values obtained in the right (blue line) and left (red line) legs consecutively, with the highest vGRF values representing the peak landing values. The first landing was registered at 1.6 s for the right limb and at 9.5 s for the left limb.

The symmetry of lower limb loading during the double-leg and single-leg vertical hop landing was evaluated on the basis of (1) the comparison of the vGRF BM values obtained in involved and uninvolved limbs in ACL-reconstructed patients, and the comparison of the vGRF BM values obtained in the dominant and nondominant limbs in the control group; (2) the analysis of the percentage of the between-limbs difference in the obtained vGRF BM values; (3) the so-called limb symmetry index (LSI) calculation with values closer to 100, indicating smaller between-limbs deficits; and (4) all of the obtained results in ACL-reconstructed patients were compared to the control group.

The LSI for each ACL-reconstructed patient was calculated by dividing the result obtained in the involved limb by the result obtained in the uninvolved limb, multiplied by 100. The LSI for each participant from the control group was calculated by dividing the result obtained in the nondominant limb by the result obtained in the dominant limb, multiplied by 100.

To avoid any potential interviewer bias, we standardized the examiner interaction with the study participants. The examiner, who was responsible for data collection and the placing of the examined patients in particular groups on the basis of postoperative physiotherapy supervision duration, was blinded.

2.6. Statistical Analysis

The number of individuals was indicated as *n*. The minimum size of the tested sample was not determined because of the retrospective design of the study. TIBCO Statistica™ (TIBCO Software Inc., Palo Alto, CA, USA) and Microsoft Office Excel 365 Personal (Microsoft Corporation, Redmond, WA, USA) were used for the statistical analysis.

The arithmetic mean and the 95% confidence interval were calculated for the particular studied features. The Shapiro-Wilk test for normality was used to study the distribution of the features. The parametric t-test for the independent samples was used for a comparison of the time between injury and ACLR, physiotherapy supervision duration, and follow-up between ACL-reconstructed patients with postoperative physiotherapy supervision for less than six months, and patients with postoperative physiotherapy supervision for six or more months. The parametric t-test for dependent samples was performed in the between-limb comparison of the obtained vGRF BM values within the studied groups. The one-way analysis of variance (ANOVA) was used to compare the vGRF BM values obtained in the ACL-reconstructed patients with postoperative physiotherapy supervision of less than six months, to values obtained in patients with postoperative physiotherapy supervision six or more months and in the control group. The ANOVA was also performed in the between-group comparison of vGRF BM between-limb percentage difference (%) and LSI. When the ANOVA result was $p < 0.050$, the post hoc Tukey's test was performed.

The linear Pearson's correlation coefficient (r) was calculated to measure the strength and direction of any linear relationships between the duration of the supervised postoperative physiotherapy in ACL-reconstructed patients and the selected parameters. The magnitudes of all of the bivariate associations were classified as negligible (0.00–0.30), low (0.31–0.50), moderate (0.51–0.70), high (0.71–0.90), and very high (0.91–1.00) [34]. Additionally, the coefficient of determination, the r -squared (r^2), was calculated to give a proportion of variance (fluctuation) of one variable that is predictable from the other variable. r^2 represents the percentage of data points that are the closest to the line of best fit.

The statistical significance was set at $p < 0.050$.

3. Results

An analysis of the manual anterior tibial translation testing results based on the Lachman test revealed no abnormalities in any of the studied participants. The pivot shift was negative in all of the studied participants.

3.1. Between-Limb and Between-Group Comparison of Obtained Vertical Hop Landing Vertical Ground Reaction Force Normalized to Body Mass (vGRF BM) Values

The analysis of the whole group of ACL-reconstructed patients indicated statistically significant differences between limbs in the vGRF BM values obtained during the double-leg and single-leg vertical hop landing (Table 2). In contrast to the ACL-reconstructed patients, there were no statistically significant differences noted between the dominant and nondominant limbs in the vGRF BM values in the control group (Table 2).

Table 2. Between-limb comparison of vertical ground reaction force values obtained during the double-leg and single-leg vertical hop landing in ACL-reconstructed patients and a control group; ACL: anterior cruciate ligament; p : level of significance of the between-limb difference; vGRF BM: vertical ground reaction force normalized to body mass. Values expressed as the arithmetic mean and 95% confidence interval.

Vertical Hop Landing vGRF BM (N·kg ^{−1})		
Total Number of ACL-Reconstructed Patients		
	Double-leg	Single-leg
Involved limb	20.17 (18.30, 22.05)	26.52 (24.37, 28.66)
Uninvolved limb	21.83 (19.93, 23.73)	27.53 (25.10, 29.96)
p	≤0.001	0.003
Control group		
	Double-leg	Single-leg
Dominant limb	24.27 (22.23, 26.30)	31.09 (29.04, 33.14)
Nondominant limb	23.96 (21.97, 25.94)	31.45 (29.41, 33.49)
p	0.483	0.313

Statistically significant between-limb differences were noted in the double-leg and single-leg vertical hop landing vGRF BM values in the patients who underwent less than months of supervised postoperative physiotherapy (Table 3). On the other hand, for the patients who underwent six or more months of supervised postoperative physiotherapy, the vGRF BM values were comparable in the ACL-reconstructed and contralateral limb.

The double-leg vertical hop landing vGRF BM values obtained in the involved limb in the patients with a shorter duration of supervised physiotherapy were significantly lower than in the involved limb in the patients with a longer duration of supervised physiotherapy, and in the dominant limb in the control group (Table 3). The results of the patients who underwent longer supervised physiotherapy were comparable to the control group. The double-leg vertical hop landing vGRF BM values did not significantly differ between the uninvolved limbs in the ACL-reconstructed patients and the nondominant limb in control group.

Table 3. Between-limb and between-group comparison of the vertical ground reaction force values obtained during the double-leg and single-leg vertical hop landing in the patients with postoperative physiotherapy supervision <6 months, patients with postoperative physiotherapy supervision ≥ 6 months, and control group; ACL: anterior cruciate ligament; *p*: level of significance of the between-limb and between-group difference; vGRF BM: vertical ground reaction force normalized to body mass. Values expressed as the arithmetic mean and 95% confidence interval.

Vertical Hop Landing vGRF BM (N·kg ⁻¹)						
ACL-Reconstructed Patients				Control Group		<i>p</i>
		Physiotherapy Supervision < 6 Months	Physiotherapy Supervision ≥ 6 Months			
Double-leg	Involved limb	17.43 (15.32, 19.53)	22.40 (19.70, 25.10)	Dominant limb	24.27 (22.23, 26.30)	≤ 0.001 ¹
	Uninvolved limb	20.86 (18.03, 23.68)	22.62 (19.89, 25.35)	Nondominant limb	23.96 (21.97, 25.94)	0.199
	<i>p</i>	≤ 0.001	0.334	<i>p</i>	0.483	
Single-leg	Involved limb	23.60 (20.61, 26.59)	28.88 (26.05, 31.71)	Dominant limb	31.09 (29.04, 33.14)	≤ 0.001 ²
	Uninvolved limb	25.42 (21.62, 29.23)	29.24 (26.01, 32.48)	Nondominant limb	31.45 (29.41, 33.49)	0.012 ³
	<i>p</i>	0.037	0.427	<i>p</i>	0.313	

¹ Patients with physiotherapy supervision < 6 months vs. patients with physiotherapy supervision ≥ 6 months, $p = 0.026$; patients with physiotherapy supervision < 6 months vs. control group, $p \leq 0.001$; patients with physiotherapy supervision ≥ 6 months vs. control group, $p = 0.455$. ² Patients with physiotherapy supervision < 6 months vs. patients with physiotherapy supervision ≥ 6 months, $p = 0.027$; patients with physiotherapy supervision < 6 months vs. control group, $p \leq 0.001$; patients with physiotherapy supervision ≥ 6 months vs. control group, $p = 0.385$. ³ Patients with physiotherapy supervision < 6 months vs. patients with physiotherapy supervision ≥ 6 months, $p = 0.199$; patients with physiotherapy supervision < 6 months vs. control group, $p = 0.009$; patients with physiotherapy supervision ≥ 6 months vs. control group, $p = 0.452$.

The single-leg vertical hop landing vGRF BM values were significantly lower in the involved limb of the patients who underwent less than six months of supervised postoperative physiotherapy than in the involved limb of patients who underwent six or more months of supervised postoperative physiotherapy and in the dominant limb in control group (Table 3). Also, the values obtained in the uninvolved limb in the patients who underwent less than six months of supervised postoperative physiotherapy were significantly lower than in the involved limb of the patients who underwent more than six months of supervised postoperative physiotherapy and in the dominant limb in control group. The results of the patients who underwent six or more months of supervised postoperative physiotherapy were similar to the results in the control group.

3.2. Between-Group Comparison of Vertical Hop Landing Vertical Ground Reaction Force Normalized to Body Mass (vGRF BM) Between-Limb Percentage Differences Values

The analysis of the double-leg vertical hop landing vGRF BM between-limb percentage differences values revealed significantly higher deficits in the ACL-reconstructed patients with postoperative physiotherapy supervision for less than six months than in patients with postoperative physiotherapy supervision for six or more months and in the control group (Table 4). The between-limb percentage differences were comparable in the patients with postoperative physiotherapy supervision for six or more months and in the control group.

Table 4. Between-group comparison of vertical ground reaction force between-limb percentage difference values obtained during the double-leg and single-leg vertical hop landing in patients with postoperative physiotherapy supervision < 6 months, patients with postoperative physiotherapy supervision ≥ 6 months, and the control group; ACL: anterior cruciate ligament; p , level of significance of the between-group difference; vGRF BM: vertical ground reaction force normalized to body mass. Values expressed as the arithmetic mean and 95% confidence interval.

Vertical Hop Landing vGRF BM between-Limb Percentage Difference (%)				
ACL-Reconstructed Patients			Control Group	p
Total Number	Physiotherapy Supervision < 6 Months	Physiotherapy Supervision ≥ 6 Months		
9.04 (6.41, 11.66)	15.55 (11.67, 19.43)	Double-leg 3.77 (2.52, 5.02)	6.52 (4.89, 8.14)	≤ 0.001 ¹
5.91 (3.94, 7.88)	6.82 (2.82, 10.82)	Single-leg 5.17 (3.32, 7.02)	5.30 (3.85, 6.76)	0.558

¹ Patients with physiotherapy supervision < 6 months vs. patients with physiotherapy supervision ≥ 6 months, $p \leq 0.001$; patients with physiotherapy supervision < 6 months vs. control group, $p \leq 0.001$; patients with physiotherapy supervision ≥ 6 months vs. control group, $p = 0.133$.

It is worth noting that in patients with postoperative physiotherapy supervision for less than six months, the between-limb percentage difference of the single-leg vertical hop landing vGRF BM values amounted only averagely 6% (Table 4), even though there was a noted statistically significant difference between the involved and uninvolved limbs in terms of the vGRF BM values (Table 3). However, as the values obtained in the involved and uninvolved limbs were significantly lower in patients with shorter supervised physiotherapy than in patients with longer supervised physiotherapy and the control group, this may be an example of a falsely low percentage difference.

3.3. Between-Group Comparison of Vertical Hop Landing Vertical Ground Reaction Force Normalized to Body Mass (vGRF BM) Limb Symmetry Index (LSI)

The double-leg vertical hop landing vGRF BM LSI was significantly lower in the ACL-reconstructed patients with postoperative physiotherapy supervision for less than months than in the patients with postoperative physiotherapy supervision for six or more months, and in the control group (Table 5). The LSI values were comparable in the patients with postoperative physiotherapy supervision of six or more months and the control group.

Table 5. Between-group comparison of vertical ground reaction force limb symmetry index values obtained during double-leg and single-leg vertical hop landing in patients with postoperative physiotherapy supervision < 6 months, patients with postoperative physiotherapy supervision \geq 6 months, and the control group; ACL: anterior cruciate ligament; p : level of significance of the between-group difference; vGRF BM: vertical ground reaction force normalized to body mass. Values expressed as the arithmetic mean and 95% confidence interval.

Vertical Hop Landing vGRF BM Limb Symmetry Index				
ACL-Reconstructed Patients			Control Group	<i>p</i>
Total Number	Physiotherapy Supervision < 6 Months	Physiotherapy Supervision ≥ 6 Months		
Double-leg				
92.52 (89.39, 95.64)	84.45 (80.57, 88.33)	99.05 (96.94, 101.16)	99.34 (95.28, 103.39)	≤0.001 ¹
Single-leg				
96.97 (94.38, 99.57)	94.03 (89.66, 98.39)	99.36 (96.34, 102.39)	101.44 (99.21, 103.68)	0.003 ²

¹ Patients with physiotherapy supervision <6 months vs. patients with physiotherapy supervision \geq 6 months, $p \leq 0.001$; patients with physiotherapy supervision <6 months vs. control group, $p \leq 0.001$; patients with physiotherapy supervision \geq 6 months vs. control group, $p = 0.994$. ² Patients with physiotherapy supervision <6 months vs. patients with physiotherapy supervision \geq 6 months, $p = 0.065$; patients with physiotherapy supervision <6 months vs. control group, $p = 0.002$; patients with physiotherapy supervision \geq 6 months vs. control group, $p = 0.537$.

The values of the single-leg vertical hop landing vGRF BM LSI were statistically significantly lower in the patients with postoperative physiotherapy supervision for less than months than in the patients with postoperative physiotherapy supervision for six or more months and in the control group. Even though such a small difference is questionable from a clinical point of view, generally, the vGRF BM values obtained in the involved and uninvolved limbs in this group of patients were lower than in the patients with longer physiotherapy supervision duration and in the control group.

3.4. Association of Vertical Ground Reaction Force Normalized to Body Mass (vGRF BM) Limb Symmetry Index and Postoperative Physiotherapy Supervision Duration

The vGRF BM LSI during the double-leg vertical hop landing was highly ($r = 0.727$; $p < 0.001$) associated with the postoperative physiotherapy supervision duration (Figure 6). The longer the postoperative physiotherapy supervision duration, the higher the LSI value, indicating a better result. The 53% of the total variation in vGRF BM LSI during double-leg vertical hop landing can be explained by the positive linear relationship between the vGRF BM LSI during the double-leg vertical hop landing and the postoperative physiotherapy supervision duration ($r^2 = 0.529$).

There was also a significant positive correlation between the vGRF [BMI] LSI during the single-leg vertical hop landing and postoperative physiotherapy supervision duration (Figure 7), but its level was low ($r = 0.333$; $p = 0.041$). Only 11% of the total variation in vGRF BM LSI during the single-leg vertical hop landing can be explained by the positive linear relationship between vGRF BM LSI during single-leg vertical hop landing and postoperative physiotherapy supervision duration ($r^2 = 0.111$). The other 89% of the total variation remains unexplained.

Additionally, we analyzed the correlation of the time between the ACL injury and ACLR with the vGRF [BMI] LSI value during the vertical double-leg hop landing ($r = 0.081$; $p = 0.628$) and the correlation of this time with the vGRF [BMI] LSI value during the vertical single-leg hop landing ($r = 0.130$; $p = 0.438$). There was no association between those studied features.

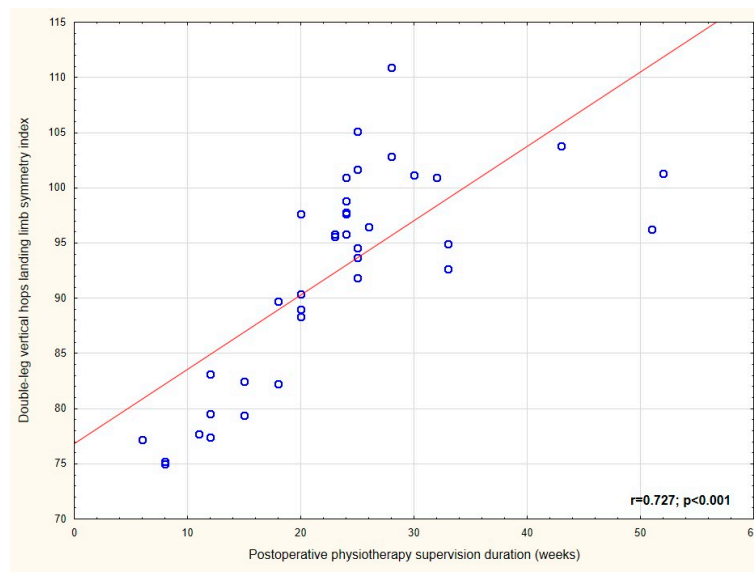


Figure 6. A significant positive correlation indicated that a higher limb symmetry index of vGRF BM during the double-leg vertical hop landing is associated with a longer duration of postoperative physiotherapy supervision in patients after ACLR.

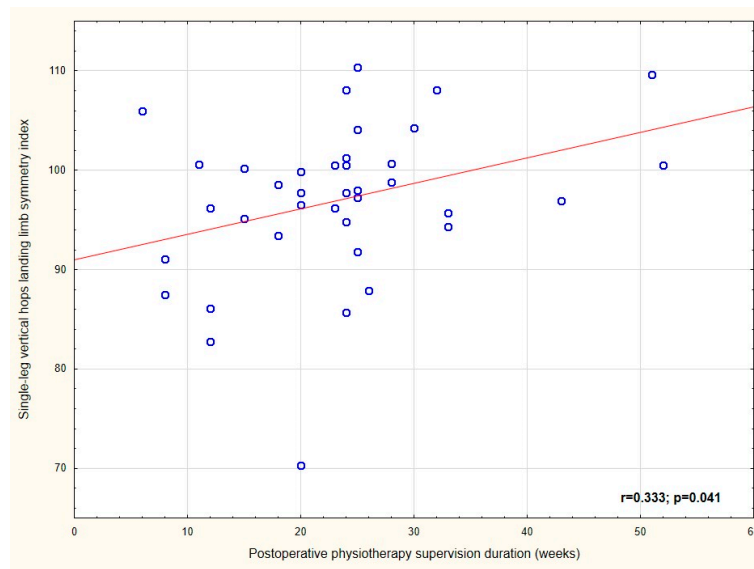


Figure 7. A statistically significant but weak positive correlation indicated that the higher limb symmetry index of vGRF BM during the single-leg vertical hop landing is associated with a longer duration of postoperative physiotherapy supervision in patients after ACLR.

4. Discussion

The goal of this study was to investigate the association of lower limb symmetry during the multi-joint task of vertical hopping performed by males who had undergone an ACLR on average two years before, and the duration of their postoperative physiotherapy was under the supervision of a specialist. The main finding of the study was that double-leg vertical hop landing limb symmetry in patients an average of two years after ACLR was correlated with postoperative physiotherapy supervision duration. The longer the postoperative physiotherapy supervision was, the higher the vGRF BM value obtained in the ACL-reconstructed limb and the higher the LSI value during the double-leg vertical hop landing. There was also a significant, although weak, association

between the single-leg vertical hop landing limb symmetry and the postoperative physiotherapy supervision duration.

In the present study, in patients whose postoperative physiotherapy was supervised for less than six months, the vGRF BM was significantly worse during the hop landing for the ACL-reconstructed limb compared to the contralateral one, and compared to the patients who underwent supervised physiotherapy for six months or more, and also compared to healthy individuals. Those findings indicate the long-term consequences of postoperative physiotherapy supervision that lasted less than six months.

Generally, there is no uniform terminology regarding unsupervised postoperative physiotherapy after ACLR, as the amount of physiotherapy input attained with so-called non-supervised or partially supervised physiotherapy is unclear. According to the opinion of some authors discussing the issue in the past, a minimally supervised postoperative physiotherapeutic procedure is cost saving [10] and can result in successful ACL rehabilitation [7,10,35,36]. This opinion has been changing [11,12]. There are studies indicating better outcomes in terms of speed and agility in patients eight months postoperatively, who underwent a physiotherapeutic procedure at a rehabilitation center and were directly supervised by a physiotherapist for at least six months after ACLR, compared to the patients with a shorter postoperative physiotherapy supervision [12]. In other studies, in patients following supervised physiotherapy for less than six months postoperatively, the two-legged landing limb symmetry was worse than that in the patients receiving fully supervised physiotherapy for at least six months, and worse than that in healthy individuals, indicating that fully supervised postoperative physiotherapy is more effective for improving two-legged vertical jump landing limb symmetry eight months after ACLR [27]. The present study confirms the influence of the postoperative physiotherapy supervision for at least six months postoperatively on the landing limb symmetry in patients after ACLR. Supervision by a specialist during the final stages of physiotherapy after ACLR, and practicing strength, power, complex movement patterns, running, and endurance training [32], seems to be crucial to restore, in particular, two-legged vertical hop landing limb symmetry two years postoperatively. Patients after knee surgery need to continue a specific program for reducing proprioceptive deficits in the long term, as returning to sports activity is not sufficient for reducing such deficits [37,38]. Even though some authors claim that home-based rehabilitation following ACL reconstruction is deleterious when prescribed to motivated patients [39], the question arises whether even the most motivated patient has the knowledge to handle with his own training without being supervised by a specialist. It is also worth adding that postoperative physiotherapeutic procedures have changed over the past couple of decades, and generally, the protocols based strictly on the time elapsed from ACLR have been replaced by criteria-based guidelines [40]. Our ACL-reconstructed patients were regularly monitored, and they were going through consecutive stages of the procedure based on objective criteria [33]. In patients with a minimum of six months of postoperative supervision, the objective monitoring of the physiotherapy progression was also longer than in the patients with shorter physiotherapy supervision. This allowed for individualization of the procedure and ensuring a safe progression through the physiotherapy.

In ACL-reconstructed patients with a postoperative physiotherapy supervision duration of less than six months, the mean vGRF BM LSI value during the double-leg vertical hop landing was lower than 90, in contrast to the patients with a longer postoperative physiotherapy supervision and with healthy individuals. The double-leg vertical hop landing vGRF BM LSI was positively associated with the duration of the postoperative physiotherapy supervision duration. The longer the postoperative physiotherapy supervision was, the higher the vGRF BM value obtained in the ACL-reconstructed limb and the higher the LSI value during the double-leg vertical hop landing. Based on the obtained coefficient of determination values, it can be seen that in the small majority of examined ACL-reconstructed patients, the double-leg vertical hop landing vGRF BM LSI can be explained by the positive linear relationship between the vGRF BM LSI during the double-leg vertical hop landing and the postoperative physiotherapy supervision duration. An abnormal LSI, which is

characterized by asymmetries between the right and left legs, should be viewed as undesirable and be remedied accordingly [41].

In the case of the single-leg hop landing in patients with postoperative physiotherapy supervision duration less than six months, the mean vGRF BM LSI value was significantly lower than in the patients with longer postoperative physiotherapy supervision duration and controls, however it was greater than 90. What is more, the positive linear relationship between the single-leg vertical hop landing vGRF BM LSI and the postoperative physiotherapy supervision duration explained the single-leg vertical hop landing vGRF BM LSI only in a tenth of the examined ACL-reconstructed patients.

On the other hand, caution is warranted for the use of LSI [25,42], as it can mask bilateral deficits, as the uninvolved limb can also be affected, and it may also be experiencing weakness after the reconstruction [25]. To prevent the possible misjudgment of the results of the performed vertical hops test, apart from the LSI analysis, the obtained values of the vGRF BM were analyzed. The analysis confirmed the significantly higher vGRF BM values obtained in the ACL-reconstructed limbs during double-leg and single-leg vertical hop landing in the patients whose postoperative physiotherapy was directly supervised by the physiotherapist for at least six months after reconstruction. On the other hand, in contrast to the results obtained during the double-leg vertical hop landing, the vGRF BM values obtained in the uninvolved limbs during the single-leg vertical hop landing were significantly lower in the patients whose postoperative physiotherapy was directly supervised for less than six months than in the patients with a longer duration of physiotherapy supervision and controls. According to that, the landing vGRF BM LSI in terms of single-leg vertical hops was falsely high in patients whose postoperative physiotherapy was directly supervised by the physiotherapist for less than six months after ACLR.

After analyzing the results obtained in the present study, the question arises as to what could have been the cause of the observed disturbances between the limbs at the time of the vertical hop landing. Alterations in the landing limb symmetry observed in the patients with less than six months of postoperative physiotherapy supervision may indicate some compensatory mechanism for ACL-reconstructed limb protection. A long-term neuromuscular asymmetry seems to be one possible reason, as several studies observed neuromuscular deficits in the ACL-reconstructed limb compared to the contralateral limb and compared to the healthy controls, even after approximately one year and longer postoperatively during different multi-joint movement tasks evaluated using force plates and three-dimensional movement analysis systems [16,17,43,44]. Paterno et al. (2010) noted that females on average two years after ACLR landed with greater force on the contralateral limb compared with the ACL-reconstructed one [16]. According to Castanharo et al. (2011), the male patients also presented a deficit in the ACL-reconstructed knee after an average of two years postoperatively, because it had its energy generation over time partially substituted by the hip joint power on the ipsilateral side [17]. Delahunt et al. (2012) observed that the ACL-reconstructed female patients at an average of four years postoperatively had greater peak hip- and knee-adduction angles, greater hip internal-rotation angles, and decreased peak knee-flexion angles compared with healthy females [29]. Bell et al. (2014) noted different landing strategies in ACL-reconstructed patients compared to healthy control participants [45] using the landing error scoring system (LESS) as an assessment tool of the jump-landing mechanics. Some authors have probably accurately suggested that whenever there is a possibility for the nervous system to substitute the function of the ACL-reconstructed limb, the nervous system will do so [17]. That would be in line with the greater between-limb asymmetries during the double-leg tasks than during the single-leg ones in the present study.

In addition, another question arises, namely, what the consequences of the altered between-limb symmetry during hop landing may be. Altered loadings of the knee joint may trigger the development of osteoarthritis and therefore influence quality of life [13,28]. Some authors also suggest that altered movement strategies in ACL-reconstructed patients are partially responsible for the high second-injury rates in this population [45]. Additional research is needed to clarify the clinical and functional importance of the observed alternations in ACL-reconstructed patients.

The small number of participants may be considered as a limitation of this study. The manual ligament laxity assessment is a possible limitation. It would have been better if the analysis had been performed with a three-dimensional motion analysis.

Taking the well-known ACL-injury gender bias into account, there remains a need for additional research on between-limb symmetry during double-leg and single-leg vertical hop landing in female ACL-reconstructed patients.

From a clinical point of view, it is possible to improve the between-limb asymmetry during the jumping task landings observed by other authors, and in one of the studied groups in the present study in physiotherapy supervised by a specialist, lasting at least six months postoperatively. The findings of the present study indicate that ACL-reconstructed patients benefit when their physiotherapeutic procedure is supervised directly by a specialist for at least six months postoperatively, as longer postoperative physiotherapy supervision more effectively improved double-leg vertical hop landing limb symmetry in the patients after ACL reconstruction to the level of healthy individuals. Going further along this line of thinking, it can be assumed that supervision by a specialist during the final stages of physiotherapy after ACLR, practicing strength, power, complex movement patterns, running, and endurance training seems to be crucial to restore two-legged vertical jump limb symmetry. An interesting aspect of this research for clinicians is that regaining the symmetry between the ACL-reconstructed and contralateral limb during double-leg hop landing may be more difficult than regaining the symmetry in terms of single-leg hop landing. On the other hand, the findings indicating the deficits in the uninvolved limb in ACL-reconstructed patients whose physiotherapy was supervised for less than six months postoperatively confirm that analyzing the symmetry alone may result in a falsely high limb symmetry, and should therefore be analyzed with caution. Additionally, the data from the present study can serve as a reference point for the analysis and interpretation of results from ACL-reconstructed males who are well trained and frequently participate in sports.

5. Conclusions

Double-leg vertical-hop-landing limb symmetry in males, an average of two years after ACLR, is highly correlated with postoperative physiotherapy supervision duration. The longer the postoperative physiotherapy supervision, the higher ACL-reconstructed limb vGRF BM values and higher LSI, indicating smaller between-limb deficits during double-leg vertical hop landing. There was also a significant, although weak, positive association between single-leg vertical hop landing limb symmetry and postoperative physiotherapy supervision duration. The present findings indicate poor long-term consequences of postoperative physiotherapy supervision that lasted less than six months, and suggest that fully supervised physiotherapy for a minimum of six months postoperatively is more effective for improving the vertical hop landing limb symmetry in patients an average of two years after ACLR.

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