DOI: 10.37190/ABB-02564-2024-02

Biomechanics of periarticular knee muscles after ACL surgery in young patients - comparison of autograft reconstruction and suture-tape augmented primary repair

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Submitted: 12th December 2024
Accepted: 30th January 2025

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Abstract

Purpose: Last years brought a growing interest in suture-tape augmented ACL repair techniques instead of ACL reconstructions with autografts due to their limited success rates. However, there is a lack of experimental studies that compare the influence of both procedures on knee periarticular muscles biomechanics. The aim of the study was to analyze periarticular muscles torque and their activity during movement for young patients after ACL repair (IB) and ACL reconstruction (ACLR), compare them with each other and with a healthy subjects (Controls).

Methods: Isokinetic torques of knee flexors and extensors and their EMG activity during gait and drop vertical jump (DVJ) were measured in 48 patients (IB – 20, ACLR – 28) at least one year after surgery and in 25 healthy controls.

Results: The muscle torques in the operated limb were lower in both group of patients comparing to Controls, but IB scored the lowest values (79% of Controls for extensors, $p=0.005$; 74% for flexors, $p=0.001$). Decrease of muscle torques in the contralateral limb occurred only in IB group (84% of Controls for both extensors ($p=0.045$) and flexors). Increased hamstrings activity were noticed for ACLR comparing to IB and Controls. The balance between activity of muscles acting on the medial and lateral side of the knee for ACLR tilts more towards the lateral side.

Conclusions: Increased hamstrings activity and changes in balance between laterally and medially located muscles indicate on the increased need for muscle support of knee stability in ACLR patients.

Keywords: knee, ACL reconstruction, Internal Brace, muscle activity, muscle torque

1. Introduction

Anterior cruciate ligament (ACL) tear is one of the most common knee injuries, especially in young, active population [3]. Currently, the gold standard of ACL injuries treatment is reconstruction with use of an autograft [22]. However, in literature variable results are being reported regarding patient's satisfaction and revision rates [23]. As a result, there is a growing interest in ACL primary repair. One of the most promising technique is a suture-tape augmented repair, for example the Internal Brace™ technique (Arthrex GmBH), (IB) [37].

The IB is a repair technique that allows to reattach and reinforce the native ligament, connecting together the proximal and distal parts of torn ACL using a lasso suture and bracing it with a high-strength suture tape [13, 17]. On the contrary, traditional ACL reconstruction leads to removing injured ligament and replacing it by autograft. The necessity of harvesting

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the graft can cause significant changes in the muscle-tendon unit morphology at the donor-site. In this context, IB technique is presented as less invasive [26] and promising method with potential advantages over reconstruction [13]. Theoretically, the muscle-tendon unit remains unaffected as the autograft is not harvested, which makes it possible to achieve less severe consequences regarding periarticular muscle strength. Moreover, IB may possibly accelerate the rehabilitation protocols and allow for earlier return to full activity due to primary stabilization effect of the suture tape [21].

On the other side, periarticular muscles play significant role as the secondary knee stabilizers [1]. As the ACL surgery result in some changes in the knee structure due to unnatural properties of the reconstructed or repaired ligament (differences in its stiffness, length, proprioception, etc.) it is highly probable, that this procedure can influence on periarticular muscle functioning and their activity during movement. Theoretically, this effect should be less prominent in the case of ACL repair as the native ligament is maintained, but all these potential advantages of IB method are still not proven experimentally. To the authors' knowledge, there are practically no studies that assess muscles strength and their activity in a comprehensive way after ACL repair. There is only one study, which is focused on gait analysis [4].

Therefore, the aim of presented study was to:

- analyze the periarticular knee muscles torques and their activity during movement in group of young patients after ACL repair with the Internal Brace™ technique (IB) and after ACL reconstruction with hamstring autograft (ACLR), compare them with each other as well as with a healthy cohort,
- answer to the question if IB method has really advantage over ACLR regarding periarticular muscle functioning.

To our knowledge, this is the first study, which addresses the issue, especially concerning group of young IB patients.

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2. Materials and method

2.1. Concept of the research

In this study two main aspects will be analyzed: (1) knee flexors and extensors strength, (2) muscles activity during movement. Muscles strength will be evaluated in the isokinetic condition, while muscle activity will be recorded during two functional tests: gait and drop vertical jump (DVJ). All tests will be performed during one measurement session lasting no longer than 120 minutes to avoid excessive fatigue of the participant. Taking into account suggestions that the intact limb of the patient after surgery cannot always be treated as a control [14, 24] a group of healthy subjects will be included in the research.

2.2. Subjects

Twenty-eight individuals after ACL reconstruction with the hamstrings autograft (ACLR), twenty patients after ACL primary repair with suture tape augmentation according to original Internal Brace™ technique (IB), and twenty five healthy subjects (Controls) participated in this study (Table 1). Patients had completed the rehabilitation process and were at least 12 months postoperatively. Participants were matched to groups so that they did not differ significantly regarding age, body mass and height.

Exclusion criteria included concomitant high grade injury of medial collateral ligament (MCL), lateral collateral ligament (LCL) or posterior cruciate ligament (PCL), meniscus repair in the injured knee, history of ligamentous/meniscal injury, or reconstruction on the contralateral knee. Additionally, exclusion criteria included also history of any injuries in contralateral knee, history of any surgeries involving lower limbs as well as any rheumatological or neurological disorders. All patients were treated in the same way, which was described more precisely in our earlier paper [10]. The most important that IB was performed only for those patients with proximal ACL avulsion within 3 weeks after an injury as well as ACL retained good tissue quality (confirmed intraoperatively). Controls were included on the basis of clinical assessment performed by orthopedist, after meeting following criteria: good general health on the day of the study, no major limb misalignment and no injury in lower limbs in the last 12 months. Participants from all groups do sports only recreationally. A written informed consent was obtained from each subject prior to data collection. The protocol of the study was approved by the Ethical Review Board R-I-002/356/2017.

Table 1. Descriptive characteristics of participants (F – female, M – male). Data are presented as mean and standard deviation [mean (SD)].

Group / **Parameter**	**Controls (n=25) 11F / 14M**	**IB (n=20) 8F / 12M**	**ACLR (n=28) 10F / 18M**	**p-value**
Age (years)	23.7 (1.7)	25.0 (10.5)	21.8 (4.8)	-
Height (m)	1.78 (0.09)	1.76 (0.11)	1.74 (0.12)	-
Mass (kg)	72.9 (13.0)	84.0 (14.5)	76.8 (16.2)	-
Time post-surgery (months)	-	28 (15)	30 (18)	-

2.3. Instrumentation and data collection

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Isokinetic test. Concentric peak torques of knee extensors and flexors were measured in isokinetic conditions using the BIODEX System 4 Pro (Biodex Medical Systems, New York, USA) at angular velocity 120°/s [15]. During test, the patient was seated in the upright position, while pelvis, chest and thigh of examined limb were stabilized with straps. The starting position was 90° of knee and 85° of hip flexion. Five practice and four recorded repetitions for both knee flexion and extension were performed, recording muscle torque for the operated (IB-op/ACLR-op), non-operated (IB-nop/ACLR-nop) limb and for both limbs for Controls.

Motion capture. For gait analysis each participant walked barefoot along a 9-metre walkway at a preferred speed. For DVJ each subject stood on 35-cm high box and were instructed to drop down to the floor and then to immediately performed a vertical jump as fast as possible without stopping. During both functional tests five proper trials (all markers were visible and jump was performed after landing without stopping) were recorded. The motion capture system (Qualisys AB, Gothenburg, Sweden) with set of 26 passive reflective markers and four cluster-tracking markers placed on the lower part of the body was used to determine the basic spatiotemporal parameters of gait and DVJ and time course of knee flexion angle.

EMG. Muscle activity of rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), semitendinosus (ST), biceps femoris (BF), and two heads of the gastrocnemius muscle (medial (GM) and lateral (GL)) were recorded using surface electromyography (EMG) (Biometrics Ltd, Newport, United Kingdom). A set of 7 integrated SX230 electrodes were placed on the tested limb [12]. The frequency of EMG data collection was set at 1000 Hz and band-pass filter was set to 20-450 Hz.

2.4. Data reduction and statistical analysis

The peak extensors and flexors torques values were normalized to a subject's body mass [Nm/kg]. Additionally, torque values obtained for ACLR and IB were compared to value obtained for Controls, and expressed as %Controls. To evaluate the symmetry of knee muscles strength between limbs, the Limb Symmetry Index (LSI) was calculated for particular muscle groups by division of the peak torque obtained for the operated limb by its value recorded for the non-operated limb [36]. Symmetrical muscle function for peak torques was defined as achieving $LSI \geq 90\%$, based on the recommendation of the European Board of Sports Rehabilitation [35].

The RMS 150 (Root Mean Square, t=150 ms) was used to obtain meaningful amplitude values from raw EMG data. The activity of analyzed muscles were normalized for each subject separately as a percentage of the arithmetic mean of peak EMG values observed for this participant in all analyzed jump repetitions (%nEMG). Additionally, these activity were

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presented as time series normalized to the gait cycle for gait (GC) and to jump cycle (JC) for DVJ (period between the first and the last feet contact with the ground). The integrated EMG (iEMG), expressing work done by muscle during GC or JC was determined (%nEMG) [7]. Additionally, a balance indexes were calculated, by dividing the temporal normalized activity of laterally situated muscle by concurrent normalized activity of medially located muscle (VL/VM, BF/ST, GL/GM, Σlateral/Σmedial), as well as balance between activity of the whole quadriceps and hamstrings (Q/H).

All results were averaged, firstly for each participant and next, for the whole group (IB-op/ACLR-op). Results for Controls were averaged for both limbs. Additionally, GC was divided into stance and swing phases, while JC for landing and propulsion phases. For statistical analysis, the muscle activities were divided at intervals of 5% of the GC or JC.

The data were checked for normality and homogeneity of variance using histograms and Shapiro–Wilk's test as well as Levene's test, respectively. The ANOVA or ANOVA Kruskal-Wallis test with the Tukey post-hoc test were used to determine differences between groups and limbs. The significance level was set to $\alpha<0.05$ and all analyses were performed using STATISTICA 13.1 (TIBCO Software Inc., USA).

3. Results

3.1. Descriptive characteristics of participants, basic spatiotemporal parameters and knee flexion angle for gait and DVJ

No significant differences were found between groups in descriptive characteristics (Table 1) and basic spatiotemporal gait and DVJ parameters (Table 2), with distinction to knee angle value at the last feet contact with the ground during DVJ (p=0.022).

Table 2. Basic spatiotemporal parameters of gait and DVJ and knee flexion angle for selected time points. Data are presented as mean and standard deviation [mean (SD)].

Parameter		Group	Controls	IB	ACLR	p-value
GAIT	Spatiotemporal parameters	Stance phase (%)	63.0 (1.5)	62.9 (1.7) ^{op}	62.0 (3.0) ^{op}	-
		Stride length (m)	0.71 (0.05)	0.67 (0.05) ^{op}	0.71 (0.08) ^{op}	-
		Stride time (s)	0.53 (0.04)	0.51 (0.05) ^{op}	0.53 (0.04) ^{op}	-
	Flexion angle	KF 0%GC (°)	2.7 (3.8)	3.5 (5.6) ^{op}	0.6 (5.3) ^{op}	-
		KF 1 (°)	22.5 (4.8)	20.6 (6.2) ^{op}	19.4 (5.5) ^{op}	-

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		KF 2 (°)	66.1 (4.9)	66.5 (5.9) ^{op}	63.3 (5.7) ^{op}	-
DVJ	Time parameters	T (s)	0.40 (0.08)	0.41 (0.11) ^{op}	0.37 (0.09) ^{op}	-
		T_L (%)	45.9 (2.2)	44.6 (3.5) ^{op}	46.1 (2.3) ^{op}	-
		T_P (%)	54.1 (2.2)	55.4 (3.5) ^{op}	53.9 (2.3) ^{op}	-
	Flexion angle	0% (°)	26.1 (5.0)	28.7 (6.3) ^{op}	25.9 (6.6) ^{op}	-
		Max (°)	83.8 (11.9)	81.6 (8.8) ^{op}	79.1 (9.9) ^{op}	-
		100 % (°)	26.0 (5.4)	23.2 (8.8) ^{op}	20.9 (10.0) ^{op}	**0.022** (Control vs ACLR-op)
	Jump height [%body height]		29.1 (5.1)	26.5 (2.9)	28.1 (4.8)	-

op operated limb, *KF 0%GC* angle value at the beginning of GC, *KF 1* the first knee flexion peak, *KF 2* the second knee flexion peak, *T* time from the first to the last feet contact with the ground, T_L landing phase time as a percentage of *T*, T_P propulsion phase time as a percentage of *T*, *0%* angle value at the first feet contact with the ground, *Max* maximum knee flexion angle, *100%* angle value at the last feet contact with the ground, *Jump height* was normalized as % of participant's body height

3.2. Knee extensors and flexors torques

Generally patient's knee muscles in the operated limb were weaker (Table 3) comparing to Controls (79%Controls – IB, 87%Controls – ACLR). IB obtained significantly lower values of extensors ($p=0.005$) and flexors ($p=0.001$) torques in both limbs, especially comparing to Controls. Simultaneously, extensors torque in ACLR-nop (2.06 Nm/kg) was significantly higher comparing to ALCR-op (1.78 Nm/kg, $p=0.030$) and even slightly comparing to Controls (101%Controls). In results, LSI value for extensors was greater for IB (96%), while for ACLR was equal to 88%. For flexors, both groups of patients achieved LSI ≥ 90% (IB – 90%, ACLR – 93%).

Table 3. Peak isokinetic knee flexors and extensors torques and LSI. Muscle torque was normalized to body weight [Nm/kg]. Data are presented as mean and standard deviation [mean (SD)].

	Extensors			**Flexors**		
Group	**mean (SD) [Nm/kg]**	**%Controls [%]**	**LSI [%]**	**mean (SD) [Nm/kg]**	**%Controls [%]**	**LSI [%]**
Controls	2.04 (0.36)	-	-	1.41 (0.27)	-	-
IB-op	1.61 (0.43)	79	**96 (19)**	1.05 (0.26)	74	**90 (15)**
IB-nop	1.73 (0.55)	84		1.19 (0.35)	84	
ACLR-op	1.78 (0.41)	87	**88 (15)**	1.22 (0.35)	87	**93 (15)**
ACLR-nop	2.06 (0.51)	101		1.33 (0.40)	94	
p-value	**0.005** (IB-op vs Controls) **0.045** (IB-nop vs Controls) **0.040** (IB-nop vs ACLR-nop) **0.030** (ACLR-op vs ACLR-nop)		-	**0.001** (IB-op vs Controls)		-

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IB anterior cruciate ligament repair, *ACLR* anterior cruciate ligament reconstruction, *op* operated limb, *nop* non-operated limb, *%Controls* percentage of the value obtained by Controls, *LSI* Limb Symmetry Index

3.3. Knee muscles activity

Muscles activities during functional tests were presented in Figure 1 and Table 4.

Quadriceps. Analyzing RF activity in IB group it was noted significantly higher activity during gait (0-15%GC) and lower during DVJ (40-65%JC). For ACLR, significant differences were observed only during DVJ (lower for 40-65%JC and higher for 85-100%JC). Regarding VL, statistically significant differences were noted only at landing phase of DVJ, where both, IB (10-35%JC and IEMG value, $p=0.029$) and ACLR (25-45%JC) reached lower activity than Controls. All patients obtained similar VM activity comparing to Controls during DVJ and higher for gait, but statistically significant increase were noted during swing phase (ACLR – 65-75%GC; IB – 65-80%GC and IEMG value, $p=0.046$).

Hamstrings. Significantly higher BF activity was noted for ACLR during gait, comparing both to Controls (0-80%GC) and IB (0-30%GC). During DVJ, higher BF activity in comparison to Controls was noted, both for ACLR (0-30%JC) and IB (0-15%JC). Significantly higher ST activity, comparing to Controls, can be observed at the beginning of gait cycle (10-30%GC) and during propulsion phase (75-100%JC) of DVJ for ACLR and IB (75-90%JC). During gait, significantly higher IEMG values were also noted in the case of ACLR, both for BF and ST, which means higher hamstrings activity in ACLR patients comparing to others.

Gastrocnemius. Both groups of patients obtained significantly higher GL activity during swing phase of GC comparing to Controls (IB – 35-45%GC, ACLR – 30-45%GC). During DVJ, IB, in comparison to Controls, obtained significantly higher GL activity for landing phase (0-10%JC) and its lower activity during propulsion phase (60-75%JC). Regarding GM, ACLR obtained significantly lower activity than others during DVJ (approx. 0-15%JC) and also during gait at the beginning (0-10%GC) and at the end (70-100%GC) of GC.

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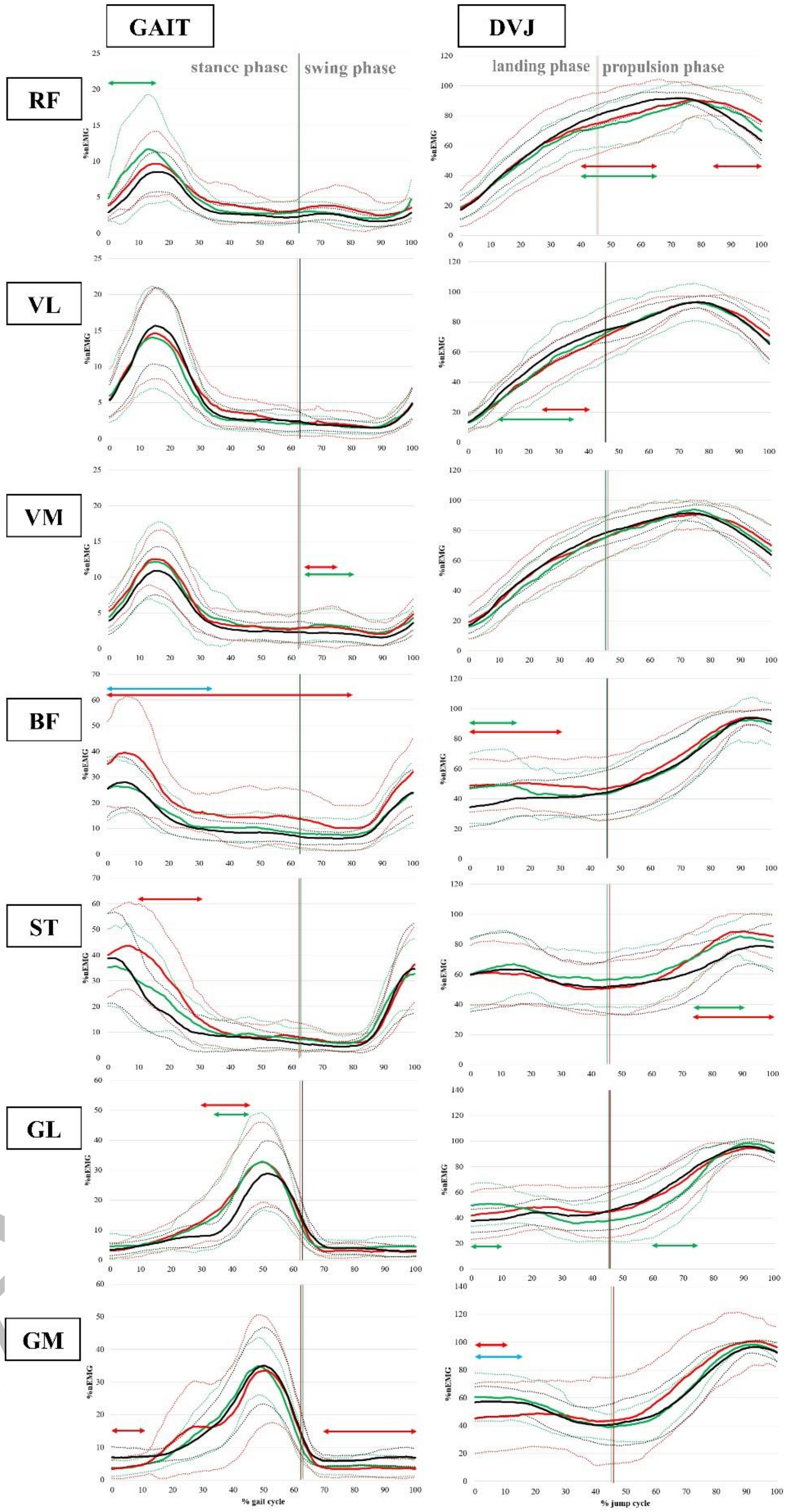

Figure 1. The waveforms of the mean activity of examined muscles during gait (left) and DVJ (right). Data for IB (green), ACLR (red) and Controls (black), expressed as %nEMG are presented as mean and standard deviation. Phases with statistically significant difference were marked with arrows (↔) ($p < 0.05$): ↔ IB/ACLR, ↔ IB/Controls, ↔ ACLR/Controls.

Table 4. IEMG values of knee periarticular muscles during GC and JC [%nEMG] calculated for IB, ACLR and Controls, presented as mean and standard deviation [mean (SD)].

Pair	Group	Gait			DVJ		
		Gait cycle	**Stance phase**	**Swing phase**	**Jump cycle**	**Landing phase**	**Propulsion phase**
		mean (SD)	**mean (SD)**	**mean (SD)**	**mean (SD)**	**mean (SD))**	**mean (SD)**
RF	**Controls**	360 (107)	279 (87)	80 (25)	6971 (291)	2464 (334)	4507 (208)
	IB-op	457 (218)	362 (182)	96 (44)	6688 (606)	2221 (467)	4468 (389)
	ACLR-op	462 (185)	340 (142)	121 (74)	6739 (692)	2308 (621)	4431 (409)
	p-value	-	-	**0.040** (ACLR-op vs Controls)	-	-	-
VL	**Controls**	519 (147)	444 (131)	75 (28)	6812 (264)	2353 (291)	4459 (227)
	IB-op	477 (204)	401 (180)	76 (38)	6438 (1004)	1951 (564)	4487 (662)
	ACLR-op	529 (196)	447 (167)	82 (50)	6605 (524)	2096 (471)	4513 (222)
	p-value	-	-	-	-	**0.029** (IB-op vs Controls)	-
VM	**Controls**	393 (156)	333 (106)	77 (40)	6877 (331)	2394 (348)	4484 (261)
	IB-op	561 (360)	430 (251)	131 (118)	6738 (548)	2134 (459)	4604 (226)
	ACLR-op	516 (183)	402 (133)	115 (93)	6906 (605)	2406 (609)	4500 (330)
	p-value	-	-	**0.046** (IB-op vs Controls)	-	-	-
BF	**Controls**	1236 (345)	854 (252)	382 (125)	5624 (1053)	1883 (540)	3741 (643)
	IB-op	1332 (485)	918 (309)	414 (224)	5853 (1132)	1998 (681)	3855 (795)
	ACLR-op	1921 (849)	1350 (596)	571 (308)	6189 (1245)	2272 (750)	3917 (656)
	p-value	**0.014** (ACLR-op vs IB-op) **0.005** (ACLR-op vs Controls)	**0.011** (ACLR-op vs IB-op) **<0.001** (ACLR-op vs Controls)	**0.013** (ACLR-op vs Controls)	-	-	-
ST	**Controls**	1378 (602)	938 (437)	440 (189)	6125 (1196)	2742 (824)	3483 (690)
	IB-op	1556 (515)	1061 (424)	495 (156)	6640 (995)	2765 (609)	3875 (712)
	ACLR-op	1786 (605)	1329 (510)	458 (175)	6398 (1011)	2613 (728)	3785 (634)
	p-value	**0.041** (ACLR-op vs IB-op) **0.030** (ACLR-op vs Controls)	**0.038** (ACLR-op vs IB-op)	-	-	-	-
GL	**Controls**	969 (322)	808 (269)	161 (72)	5958 (869)	1938 (462)	4021 (478)
	IB-op	1127 (566)	957 (485)	169 (105)	5719 (1060)	1991 (531)	3727 (657)
	ACLR-op	1117 (437)	985 (386)	132 (59)	6028 (945)	2140 (708)	3887 (592)
	p-value	-	-	-	-	-	-
GM	**Controls**	1262 (491)	1095 (319)	247 (71)	6062 (881)	2304 (394)	3757 (626)
	IB-op	1250 (289)	1068 (242)	182 (117)	6165 (817)	2370 (601)	3795 (391)
	ACLR-op	1215 (565)	1064 (528)	150 (89)	5844 (1268)	1996 (880)	3848 (566)
	p-value	-	-	**0.014** (ACLR-op vs Controls) **0.041** (IB-op vs Controls)	-	-	-

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3.4. Knee muscles balance analysis

Analyzing the knee muscles balance (Figure 2) it can be observed that generally for ACLR balance tilts more towards the lateral side (higher value of the index) comparing to Controls and IB, both for particular muscles pairs and for summary Σlateral/Σmedial index. As regards knee extensors, the value of VL/VM index for both groups of patients, remains below the level obtained for Controls, both for gait and DVJ. The exception is the second part of the stance phase of GC, where VL/VM index value for ACLR is higher comparing to Controls and even significantly higher comparing to IB (30-50% GC). For knee flexors (BF/ST, GL/GM) greater variability of results occurs, but generally ACLR group reached higher values of balance indexes than Controls, while IB obtained more similar or lower values of balance indexes comparing to Controls.

Analyzing balance between quadriceps and hamstrings (Q/H) it can be noted that all patients obtained lower values of balance index comparing to Controls, both for gait and DVJ, which is mainly the results of higher hamstrings activity. For ACLR difference is even statistically significant at the beginning of GC (15-30%GC).

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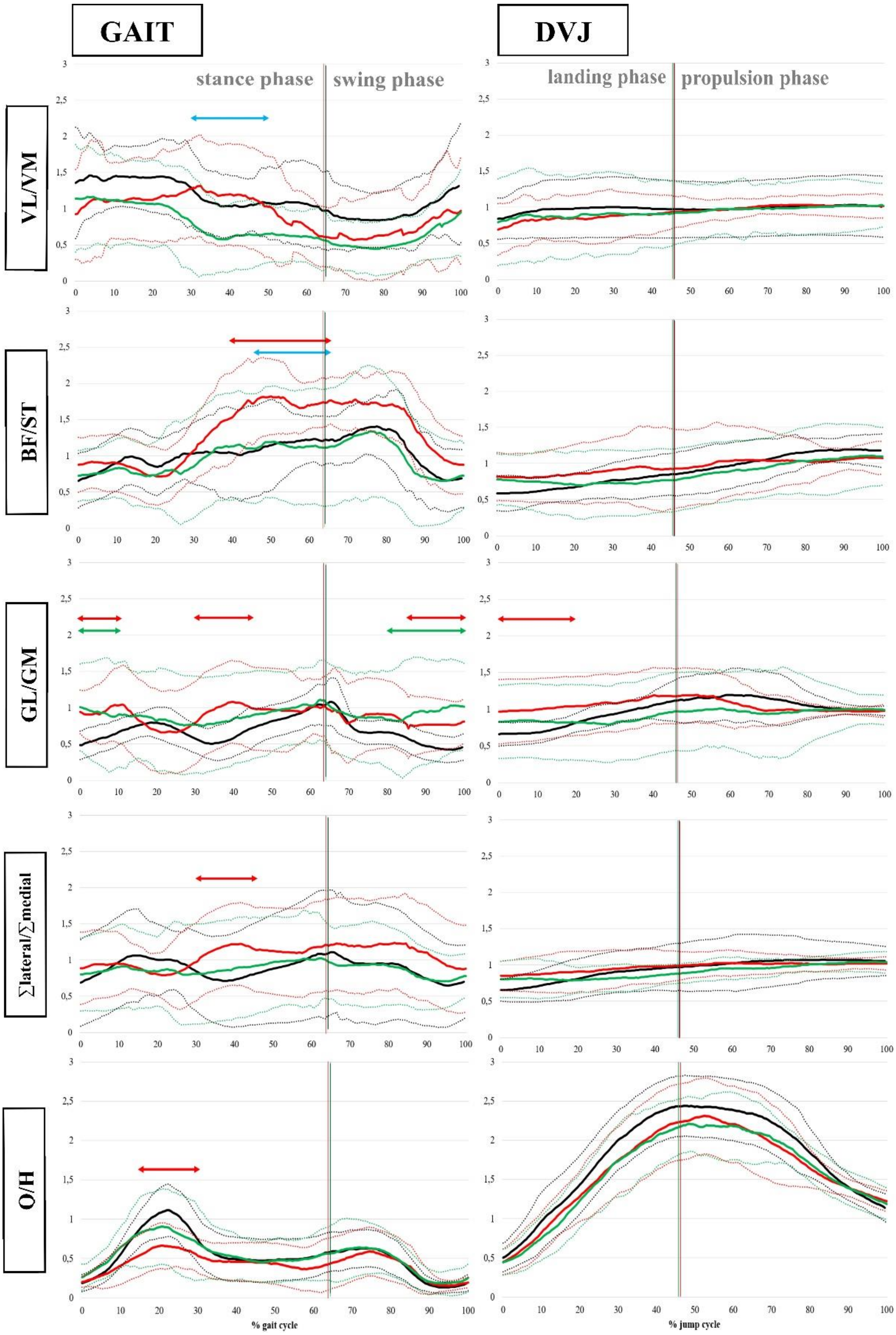

Figure 2. Balance indexes for VL/VM, BF/ST and GL/GM as well as summary index Σlateral/Σmedial and Q/H index during gait (left) and DVJ (right) – data for IB (green), ACLR (red) and Controls (black), presented as mean and standard deviation. Phases with statistically significant difference were marked with arrows (↔) ($p < 0.05$): ↔ IB/ACLR, ↔ IB/Controls, ↔ ACLR/Controls.

4. Discussion

The most important finding of our study is that after ACL surgery, despite completed rehabilitation program, periarticular knee muscle have lower ability to generate torque. Apart from that, changes in their activity during gait and DVJ may be observed.

Interestingly, whereas for ACLR muscle weakness was observed only in the operated limb, both lower extremities were affected for IB. In result, IB reached LSI value above 90%, which can be positive in the aspect of return to sport [35]. However, the decrease of the ability to generate muscle torques is a negative phenomenon and may indicate the presence of muscle strength deficits also in the uninjured limb [14, 24]. Weakness of the quadriceps [5, 6, 11, 25] and hamstrings [5, 8, 20, 29] muscles for ACLR is a generally well- known. Interestingly, we also found significantly reduced muscle torques in both limbs of IB, compared to Controls and ACLR. Potentially, patients from IB group could had weaker extensors and flexors muscles even before the surgery, comparing to ACLR patients. However, as the main criteria used for patient qualification for IB procedure were ACL good tissue quality and short enough period after injury, no patient selection based on knee muscles forces were performed. It seems, it is interesting topic for further examination. At the same time, some studies shown that the higher force produced by quadriceps, the higher loads acting on the ACL [18], so lower extensors torques could potentially protect ligament healing. For flexors this phenomenon is not entirely clear. Müller et al. also noticed significantly lower extensors torques for patients comparing to Controls, but no statistical differences between groups for flexors were observed [21].

As it was previously mentioned, some important changes in the muscle activity during movement were observed. It may be partially explained by the need to compensate deficits in the muscle torques. On the other hand, it may result from affected neuromuscular control. Comparing knee flexors and extensors, increased activity of the first group comparing to the second may be observed in ACLR (Figures 1 and 2). These patients obtained noticeable higher hamstrings activity while quadriceps activity remained on the level similar to Controls. In results, Q/H balance index was significantly lower for ACLR comparing to Controls. It is known that the hamstrings muscles show synergistic actions to ACL and prevent excessive anterior tibial translation [16], so reduced hamstrings activation is considered to be a risk factor of ACL injury [33]. On the other hand, the increased hamstrings activity and its duration is a common compensatory mechanism for the ACL absence or persistent laxity [30–32]. It may be observed even after the ACL reconstruction, because the muscle volume is reduced, or the stability of the knee has not been fully restored [19]. It is possible, that increased hamstrings activity visible in our results confirm the need for providing additional knee joint stabilization,

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in the sagittal plane, during gait for ACLR patients. However, if increased flexors activity will be accompanied by their co-contraction with extensors it may lead to knee stiffness, which is a known phenomenon for ACLR patients [9].

As it was presented above, primarily for ACLR but partly for IB patients also, increase activity of the whole knee flexors group was observed. However, this phenomenon did not occur evenly for BF and ST muscles. In result, about 1.5-fold higher value of BF/ST index value can be observed in the second part of GC (40-100%GC) for ACLR compared to other groups, which was mainly due to a greater increase in BF activity. BF/ST index value for IB was similar to Controls during gait, which can be a positive sign. Less visible changes can be observed during DVJ, where for landing phase the BF/ST ratio in IB group remains slightly below the value obtained for ACLR, while for propulsion phase BF/ST index was at a similar level in both groups of patients, remaining at a lower level comparing to Controls (Figure 2).

Taking into account knee extensors, generally both ACLR and IB patients achieved lower VL/VM balance index values than Controls, which was mainly the results of the lower VL activity during gait and DVJ. However, for ACLR opposite phenomenon was observed in the second part of the stance phase (20-60%GC), when VL/VM index value was higher comparing to Controls and IB. This effect remain in coincidence with higher value of BF/ST index in this period, and in result summary index Σlateral/Σmedial value remains higher for ACLR comparing to IB and Controls (30-100%GC). Peel et al. using a musculoskeletal model noticed that VL has the greatest effect on ACL loading [27], so lower activity may be an attempt to reduce its effect on the ACL. It is known, that during single support phase of GC, the activity of laterally located muscles is necessary to balance the gravitational forces acting on the medial compartment of the knee. This effect supports the ACL's function. Higher activity of the lateral thigh muscles, noticed for ACLR in our research in the second part of the GC, can be interpreted as the need for providing additional knee joint stabilization and ACL support in the frontal plane during gait. As the dynamic knee varus/valgus deformity presented no significant differences between ACLR and IB group in our research [10], this enhanced activity of the laterally located thigh muscles seems to be efficient enough.

For gastrocnemius actons similar activity was obtained in both groups of patients during gait, as well as earlier and longer GL activation was noticed comparing to Controls. Rhim et al. [28] stated, that gastrocnemius reaction time was significantly faster after ACL reconstruction, what allows to increase joint stability. During gait we observed similar GL/GM balance index value for both IB and ACLR, but higher comparing to Controls. In the case of DVJ, increase of GL/GM balance index value can be observed for the whole landing phase for ACLR, while in

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IB group it remains slightly below the level obtained for Controls in the final part of landing phase. However, it is also worth noting that studies do not agree on gastrocnemius importance [34] – some of them suggest a protective role for the ACL [28]. but others attribute an antagonistic role to the ACL [2]. However, the time coincidence of the increased GL/GM balance index value for ACLR patients with similar results for VL/VM and BF/ST pairs of muscles indicates the co-operation of the gastrocnemius muscles in supporting the ACL for providing knee stability.

Presented study has some limitations. Our IB group was slightly older (25.0±10.5) than ACLR (21.8±4.8), as well as heavier than others, but not significantly. Additionally, this study include patients at least 12 months post-surgery, so the findings may not be applicable to the early post-operative rehabilitative stages. Moreover, we have not known yet whether presented changes may persist, aggravate or disappear in a long-time follow-up.

5. Conclusions

To summarize, changes in muscle strength and their activity may be observed in patients after ACL surgeries in comparison to healthy controls.

Firstly, patients knee periarticular muscles were weaker in isokinetic test comparing to healthy individuals. The greatest strength deficit was observed for IB (about 20%), and surprisingly the loss of muscle torque was observed also in non-operated limb. As the advantage of such situation is possibility to achieve the acceptable LSI value, when for knee extensors in ACLR it remains below proper level.

Secondly, increased hamstrings activity were noticed for ACLR, comparing both to IB and Controls which can be correlated with enhanced importance of muscle in providing knee joint stabilization. IB patients takes advantage over ACLR in this aspect.

Thirdly, for ACLR the balance leans more towards the lateral side, especially the second part of the gait cycle (30-100% GC). This phenomenon may indicate on the increased need for muscle support in providing knee stability in frontal plane for ACLR patients.

Summing up, the answer to the question if IB method has advantage over ACLR as regards periarticular knee muscle biomechanics is not entirely clear, as both methods have some adverse effects as regards muscle strength deficit and theirs activity during movement.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Acknowledgements

Research was performed as a part of project WZ/WM-IIB/5/2023 and financed with use of funds for science from Polish Ministry of Science and Higher Education.

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