MEDICAL SCIENCE MONITOR

CLINICAL RESEARCH

e-ISSN 1643-3750
© Med Sci Monit, 2018; 24: 4882-4893
DOI: 10.12659/MSM.908411

Received: 2017.12.06
Accepted: 2018.03.25
Published: 2018.07.14

Two-Plane Assessment of Knee Muscles Isometric and Isokinetic Torques After Anterior Cruciate Ligament Reconstruction

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
Literature Search F
Funds Collection G

ABCDEFG 1 **Andrzej Czamara**
BCDEF 2 **Aleksandra Królikowska**

1 The College of Physiotherapy in Wrocław, Wrocław, Poland
2 The Center of Rehabilitation and Medical Education, Wrocław, Poland

Corresponding Author: Andrzej Czamara, e-mail: a.czamara@wsf.wroc.pl
Source of support: Departmental sources

Background: We tested the hypothesis that, in patients participating in 17 weeks of postoperative physiotherapy after anterior cruciate ligament reconstruction (ACLR), maximal isometric torque (IT) and peak torque (PT) generated by the muscles affecting the operated knee joint in the sagittal and transverse planes are not restored. We also present the application of IT and PT measurements of the muscles affecting the knee joint in 2 planes of motion.

Material/Methods: IT and PT of the knee extensor and flexor muscles and the muscles internally rotating the shin were measured in 30 males who participated in postoperative physiotherapy for 17 weeks after ACLR (ACLR group) and 30 males with no injuries (control group).

Results: Significantly lower IT and PT values were noted in the operated knee extensors and flexors. The differences were also noted in the PT for the muscles internally rotating the shin and in the IT of those muscles in the position of 25° of internal rotation. Significantly lower relative IT and PT values were noted for studied muscle groups in comparison to the control group.

Conclusions: Seventeen weeks of postoperative physiotherapy after ACLR did not result in complete restoration of IT and PT of the muscles affecting the operated knee joint, suggesting that even after 17 weeks of physiotherapy following ACLR, athletes may not be ready to return to sports. The results demonstrate the usefulness of biplanar analysis of muscle strength under isometric and isokinetic conditions in the monitoring and assessment of physiotherapeutic procedures.

MeSH Keywords: **Anterior Cruciate Ligament Reconstruction • Knee Joint • Torque**

Full-text PDF: https://www.medscimonit.com/abstract/index/idArt/908411

4722 5 8 56

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

Background

Assessment of the results of arthroscopic anterior cruciate ligament (ACL) reconstruction (ACLR) is based on orthopedic history-taking and medical examination [1–6]. Functional tests are also carried out to assess the level of postoperative restoration of motor abilities, neuromuscular coordination, and physical fitness [7–10]. One of the tasks of postoperative physiotherapy is to restore baseline torque, in adequate proportions, to the muscles affecting the operated knee joint. In publications dealing with this issue, the torque of muscle groups affecting the operated knee joint in the sagittal plane is the most frequently reported [11–20]. Few publications have analyzed torque and its reciprocal relationships in the muscles responsible for shin axial rotation (i.e., in the transverse plane) after ACLR [21–25]. There are even some data on the peak torque produced by the muscles acting on the shin in relationship to the thigh, both in the sagittal and the transverse planes, after ACLR, but they concern only isokinetic conditions and they present long-term follow-up [26].

ACL injuries often occur during dynamic multi-planar movements involving knee joint flexion and valgus stress, as well as excessive shin rotation [27,28]. Therefore, the return to sports training and competition after ACLR requires recovery of knee joint stability and normal multi-planar static and dynamic functions to prevent reinjures and repeated costs of surgery, physiotherapeutic treatment, and absence from work [29].

In the literature, it is difficult to find studies concerning the maximal isometric torque and peak torque under isokinetic conditions generated by the muscles affecting the operated knee joint in the sagittal and transverse planes at 17 weeks after ACLR. Despite progress in the understanding of graft healing, graft reconstruction, and the biomechanical determinants of these processes, therapeutic teams can feel pressured to make a patient fit enough to enable a return to dynamic sports, which will impart a substantial load on the knee joint in more than 1 plane of movement, at 4 months after ACLR. Premature return to sport activities may be one of the factors contributing to the high rate of overuse injuries in knees with a reconstructed ACL [30]. Kruse et al. (2013) focussed on the fact that the result of postoperative physiotherapy after ACLR is influenced not only by time. To this end, they list a number of elements that should be taken into consideration, including postoperative bracing and type of exercise and home-based rehabilitation, as well as neuromuscular training, strength training, and other therapeutic methods [31]. Saka et al. (2014) performed a literature review on the role of early restoration of ROM using neuromuscular electrical stimulation, proprioception, and open- and closed-chain exercises, finding that guidelines for rehabilitation after ACLR often focus mainly on time from ACLR. Such an approach facilitates the implementation of the program, but does not cover all patients, and each patient responds to the process differently. ACL rehabilitation guidelines in the future will focus on introducing physiotherapy techniques instead of time [32]. According to a review by Wright et al. (2015) concerning the ACLR rehabilitation, the question remains whether patients can be ready to return to sports at less than 4 months postoperatively, and there still is little or no scientific evidence to support this earlier return [33].

The present study tested the hypothesis that, in male patients participating in 17 weeks of postoperative physiotherapy after ACLR, maximal isometric torque (IT) and peak torque under isokinetic conditions (PT) generated by the muscles in the operated knee joints are not restored. The study also presents an application of IT and PT measurements of muscles affecting the knee joint in the sagittal and transverse planes.

Material and Methods

Participants

The study was conducted at the College of Physiotherapy in Wroclaw, Poland, and the Center of Rehabilitation and Medical Education in Wroclaw, Poland. The study was approved by the local ethics committee. Written informed consent forms were signed by all participants prior to the study, which was conducted according to the ethics guidelines and principles of the Declaration of Helsinki. The initial sample comprised 54 male post-ACLR patients who presented in the years 2012 and 2013 to the physiotherapy center where the study was conducted (Figure 1). Because of the lack of the output data of the examined patients from the period before the ACLR, an additional control group was created that included participants appropriately selected for the studied patients in terms of sex, body composition, and the level of physical activity. The control group included 30 healthy male volunteers who were recruited from among students at the college where the study was conducted. In the ACLR group, the time between the ACL injury and reconstruction did not exceed 3 months. None of the patients examined participated in physiotherapy between the injury and reconstruction, as the maximum of physical capacity occurs at 20–30 years of age [34].

We excluded 24 patients from the study due to: preoperative injury of the second leg (n=2), preoperative injuries to operated knee joint cartilage (n=6), preoperative additional injuries to the collateral ligaments of the operated knee joint (n=5), preoperative additional injuries to the meniscus/menisci of the operated knee joint (n=5), and withdrawal from physiotherapy before the 17th week due to causes beyond our control (n=6) (Figure 1). Preoperative injury of the second leg would influence the within-group comparison. Preoperative injuries

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

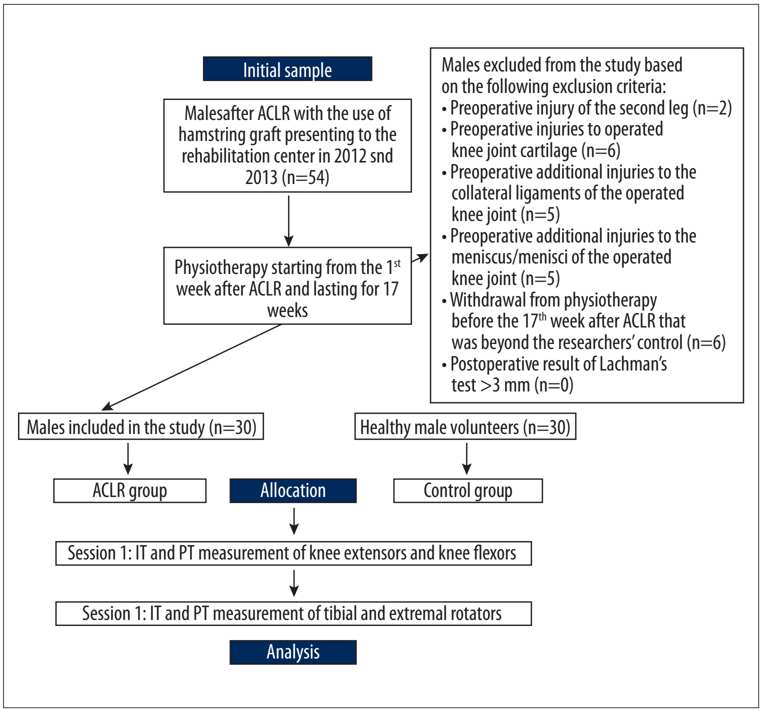

Figure 1. Flowchart of the study. ACLR – anterior cruciate ligament reconstruction; IT – isometric torque; PT – peak torque; n – total number of individuals in the sample.

Table 1. Characteristics of the study subjects.

	Age (years)		Body mass (kg)		Body height (cm)	
	$\bar{\chi}$	SD	$\bar{\chi}$	SD	$\bar{\chi}$	SD
ACLR group (n=30)	30.23	9.80	84.00	10.42	182.80	7.81
Control group (n=30)	23.70	3.17	81.70	8.78	183.40	7.28
p	0.003		0.359		0.759	

ACLR – anterior cruciate ligament reconstruction; SD – standard deviation; $\bar{\chi}$ – mean; p – level of significance.

to operated knee joint cartilage, preoperative additional injuries to the collateral ligaments of the operated knee joint, and preoperative additional injuries to the meniscus/menisci of the operated knee joint impose changes in the physiotherapeutic procedure that can influence the within-group and between-group comparisons. Some of our patients started the postoperative physiotherapeutic program but decided to end it before the week 17 measurements were performed, mostly for personal reasons like cost or changing place of residence.

The results of the final sample comprising 30 males who underwent arthroscopic ACLR (ACLR group) were compared with the results of 30 males with no injuries to the lower limbs (control group). In the ACLR group, reconstruction was performed using an autologous graft from the tendons of the ipsilateral semitendinosus muscle (single-bundle reconstruction, n=17) or semitendinosus and gracilis muscles (double-bundle reconstruction, n=13). The anamnesis revealed that the ACLR group had performed recreational activities at level 7, according to the Tegner Activity Scale [35], preoperatively. The same level of physical activity was noted in the control group participants. Characteristics of the study participants are presented in Table 1. It is worth noting that there was a statistically significant difference in terms of age of the patients and controls; however, most of the participants in both groups were 20–30 years old, so the difference should not have influenced the comparison between the studied groups.

The measurements were performed during the third stage of the postoperative rehabilitation procedure performed in the rehabilitation center [36]. The average frequency of participation in the rehabilitation was 3.63 sessions per week. One session lasted for 2 h.

Stage I (1–5 weeks postoperatively)

Patients used ice packs, replaced after several days with local cryotherapy. They practiced continuous passive motion (CPM)

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

Figure 2. The starting position of the torque measurement of muscles responsible for internal and external shin rotation in the knee joint and the starting position of the training of muscles internally rotating shin towards femur in the operated knee joint on the Humac Norm Testing and Rehabilitation System.

Figure 3. Lying-down leg curls with the shin internally rotated towards the femur in the knee joint.

exercises of the involved joint. Mobilization of the patellofemoral joint was performed. Electrostimulation of the vastus medialis and magnetic field was applied. They performed proprioceptive exercises in a closed kinematic chain (CKC), isometric tensions of the quadriceps and flexor muscles of the involved knee joints and other large-muscle groups, followed by isometric exercises with manually adjusted resistance of muscle groups beyond the area of the operated knee joint, the uninvolved lower extremity, upper extremities, and the trunk.

Stage II (6–12 weeks postoperatively)

Walking on a treadmill was added. The CPM device was replaced with exercises on a cycle ergometer. Proprioceptive exercises were performed with assistance on a soft surface. We also added exercises on a stair-stepper, squats with both legs and 1 leg on a soft surface, and concentric and eccentric exercises that were gradually increased for ischiotibial muscles of the operated leg in the sagittal plane and gradually increased in the sagittal plane with the shin internally rotated against the femur.

Stage III (13–20 weeks postoperatively)

Isometric exercises with partial resistance of the involved knee joint extensor muscles on Biodex-3 system were added. At 13 weeks after ACLR, they also performed isometric exercises with partial resistance of muscles internally rotating the shin towards the femur in the operated knee joint on the Humac Norm Testing and Rehabilitation System (Figure 2). After week 16 postoperatively, the same exercises were performed under isokinetic conditions. Running on a treadmill was introduced. Sport-specific exercises and plyometric exercises were performed. Functional training with movement pattern corrections and core exercises were added. Once or twice a week, the exercises were followed by centrifugal massage. From week 16 postoperatively, isokinetic strength training was performed. Gradually, the exercises of knee flexors with manually applied resistance with the shin internally rotated against the femur in the knee joint were replaced by leg curls lying down, with the same position of the shin (Figure 3).

All participants from the ACLR group continued the rehabilitation according to a 4-stage procedure [36].

Procedures

Testing was conducted in 2 sessions held 3 days apart at the same time of day. Each session began with a 12-min warm-up on a cycle ergometer. In the ACLR group, measurements were taken during week 17 after ACLR. The uninvolved limb was examined first, then the operated limb. In the control group the dominant leg was measured first. Participants were required to abstain from all strenuous exercise for at least 24 h prior to testing. They were instructed not to make any changes in their diet and were encouraged to drink water before testing. They were also instructed to avoid eating within 2 h before the test. All measurements were performed by the same researcher.

Session 1: Measurements of IT and PT of knee extensors and flexors

The measurements of IT of extensor (Q) and flexor (H) muscles of the knee joint were performed using a UPR-1 dynamometer (SUMER, Poland). During IT measurement of knee extensors, participants were stabilized in the supine position with 70 degrees of knee flexion (Figure 4). During measurement of

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

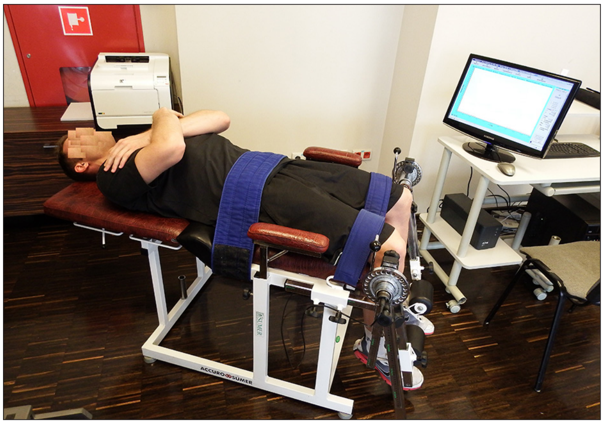

Figure 4. The starting position of the isometric torque measurement of knee extensors.

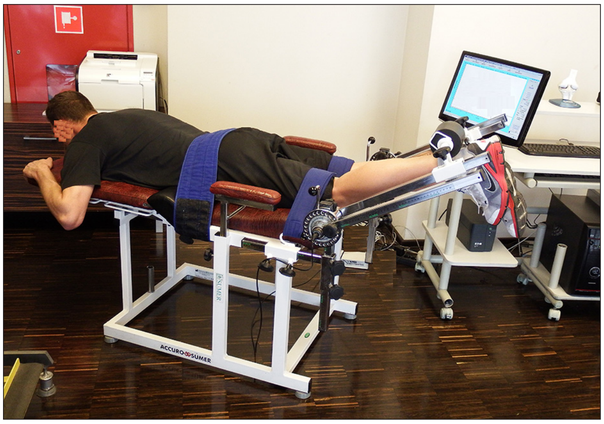

Figure 5. The starting position of the isometric torque measurement of knee flexors.

knee flexors, they were stabilized prone with 30 degrees of knee joint flexion (Figure 5). Because the body height of participants was similar, a 42-cm lever arm was used for each. Two repetitions of maximal isometric tension were performed alternately for each studied muscle group in each leg. The duration of muscle tension was 6 s. The highest IT value obtained for a given muscle group was selected for analysis [37]. The interval between IT and PT measurement was 10 min.

PT was measured using the Humac Norm™ Testing & Rehabilitation System (CSMI Computer Sports Medicine, Inc., Stoughton, MA, USA). Measurements were taken with the participant stabilized in the sitting position with 90 degrees of hip flexion (Figure 6). The length of the lever arm was 42 cm. The series of exercises performed with constant angular velocity of 180 degrees/s involved 10 repetitions of alternating extension and flexion of the knee joint. The series, performed with constant velocity of 60 degrees/s, involved 5 repetitions of alternating extension and flexion movements of the knee joint. The length of the interval between the 2 series was 120 s [36].

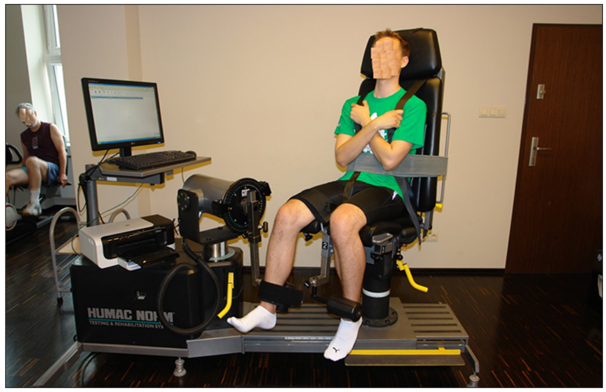

Figure 6. The starting position of the torque measurements of knee extensors and flexors under isokinetic conditions.

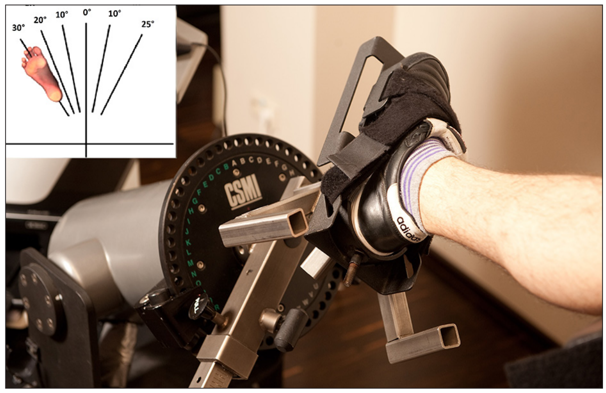

Figure 7. The starting position of the isometric torque measurements of muscles rotating the shin towards the femur in the knee joint in 30 degrees of external rotation. ER – external rotation of the shin towards the femur; NP – neutral position of the shin towards the femur; IR – internal rotation of the shin towards the femur.

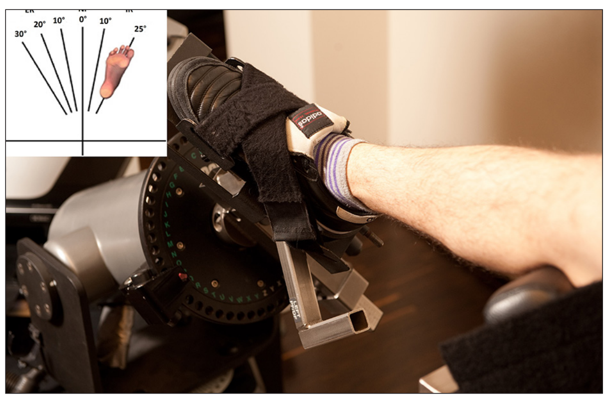

Figure 8. The starting position of the isometric torque measurements of muscles rotating the shin towards the femur in the knee joint at 25 degrees of internal rotation. ER – external rotation of the shin towards the femur; NP – neutral position of the shin towards the femur; IR – internal rotation of the shin towards the femur.

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

Table 2. Comparison of IT and PT values of knee extensors and flexors between the operated and the uninvolved legs in the ACLR group and between the operated leg (ACLR group) and the dominant leg (control group).

Torque (angular velocity)	Muscle group	Absolute IT and PT values (N·m)					Relative IT and PT values (N·m/kg of bm)				
		ACLR group				p	ACLR group		Control group		p
		Operated leg		Uninvolved leg			Operated leg		Dominant leg		
		$\bar{\chi}$	SD	$\bar{\chi}$	SD		$\bar{\chi}$	SD	$\bar{\chi}$	SD	
IT (0°/s)	Q	224.19	61.96	305.65	65.15	**<0.001**	2.68	0.69	3.88	0.88	**<0.001**
	H	109.58	27.95	119.59	30.43	**<0.001**	1.29	0.28	1.81	0.41	**<0.001**
PT (60°/s)	Q	159.93	41.86	229.93	40.12	**<0.001**	1.90	0.39	2.72	0.45	**<0.001**
	H	110.73	24.92	130.17	21.24	**<0.001**	1.32	0.25	1.62	0.27	**<0.001**
PT (180°/s)	Q	113.03	31.28	157.63	27.73	**<0.001**	1.35	0.32	2.01	0.31	**<0.001**
	H	75.73	18.69	87.60	15.37	**<0.001**	0.91	0.21	1.15	0.25	**<0.001**

ACLR – anterior cruciate ligament reconstruction; bm – body mass; H – knee flexors; IT – maximal isometric torque; PT – peak torque; Q – knee extensors; SD – standard deviation; $\bar{\chi}$ – mean. Values in bold are statistically significant.

Session 2: Measurements of IT and PT of muscles rotating the shin in the knee joint

Measurements of IT and PT were taken using the Humac Norm™ Testing & Rehabilitation System (CSMI). The patient was stabilized in supine position at baseline. The examined knee was in 80 degrees of flexion, with 90 degrees between the foot and the shin and 80 degrees of hip flexion (Figure 2).

IT was measured in 30 degrees of external rotation (ER 30°) (Figure 7) and 25 degrees of internal rotation (IR 25°) (Figure 8) of the tibia. The measurement in each position of shin rotation angle involved maximal isometric tension of the internal rotation muscles (IRM) followed by maximal isometric tension of the external rotation muscles (ERM). The duration of a single tension was 6 s. There was a 45-s interval between each tension [23]. The interval between IT and PT measurement was 10 min.

The first series of PT measurements involved 5 repetitions of alternating internal and external shin rotation with a preset angular velocity of 60 degrees/s. The second series involved 8 repetitions with a preset angular velocity of 180 degrees/s, with a 90-s interval between series [23,25].

Statistical analysis

IBM SPSS Statistics for Windows, Version 20.0 (IBM Corp., Armonk, NY) was used for statistical analysis. Mean ($\bar{\chi}$) and standard deviation (SD) were determined. Comparison of ACLR and control group results required that the IT and PT values be normalized to body mass (bm) and expressed in N·m/kg bm (relative torque) [38]. To verify the normality of distribution of the studied variables, the Shapiro-Wilk test was applied [39]. In cases of any abnormalities in the distribution ($p<0.05$), a non-parametric test was applied for the assessment of the differences between the ACLR group and the control group; when the Shapiro-Wilk test determined that the p value was >0.05, a parametric test was performed. Parametric or non-parametric testing was performed to compare dependent samples using the *t* test or Wilcoxon rank-sum test, respectively, and for between-group comparison (ACLR and the control group) we used the *t* test or the Mann-Whitney U test, respectively. Levene's test for variance homogeneity was also applied. The significance level was set at $p<0.05$. Because in 20 out of 30 ACLR cases the dominant leg was operated on, the results obtained for this leg were used for between-group comparison.

Results

During week 17 of physiotherapy, significantly lower torque values were noted in the extensors and flexors of the operated knee joints than in the uninvolved knee joints for both the isometric and isokinetic tests (Table 2). Significantly lower relative torque values were also noted for the muscle groups of the operated knee joints in the ACLR group than in the dominant legs in the control group (Table 2).

In the ACLR group, IT values for the shin internal rotators in the operated leg were significantly lower than those in the uninvolved leg in the IR 25° position (Table 3). No significant differences in IT were found between the operated and the uninvolved leg in the ER 30° position or for the muscles rotating the shin externally in either the ER 30° or IR 25° position (Table 3). No differences in IT were noted between the operated leg in the ACLR group and the dominant leg in the control group. Both absolute and relative PT values for shin internal

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

Table 3. Comparison of IT and PT values in shin internal and external rotators between the operated and uninvolved legs (ACLR group) and between the operated leg (ACLR group) and dominant leg (control group).

Torque (angular velocity)		Studied muscle group	Absolute IT and PT values (N·m)					Relative IT and PT values (N·m/kg of bm)				
			ACLR group					ACLR group		Control group		
			Operated leg		Dominant leg		p	Operated leg		Dominant leg		p
			$\bar{\chi}$	SD	$\bar{\chi}$	SD		$\bar{\chi}$	SD	$\bar{\chi}$	SD	
IT (0°/s)	ER 30°	IRM	48.17	13.66	50.83	11.51	0.098	0.57	0.12	0.61	0.11	0.136
		ERM	24.40	8.93	25.23	8.35	0.442	0.29	0.10	0.33	0.08	0.134
	IR 25°	IRM	19.37	8.22	22.23	8.56	**0.026**	0.23	0.10	0.25	0.08	0.323
		ERM	41.13	10.60	40.97	9.24	0.889	0.49	0.10	0.53	0.11	0.164
PT (60°/s)		IRM	35.53	7.25	39.93	7.55	**<0.001**	0.42	0.07	0.48	0.11	**0.024**
		ERM	34.13	7.54	38.87	8.06	**<0.001**	0.41	0.07	0.47	0.08	**0.001**
PT (180°/s)		IRM	29.03	5.61	31.53	5.96	**0.007**	0.35	0.06	0.46	0.08	**0.004**
		ERM	28.20	5.38	31.37	6.72	**<0.001**	0.34	0.06	0.41	0.06	**<0.001**

ACLR – anterior cruciate ligament reconstruction; ER 30° – knee position in 30-degree shin external rotation; ERM – knee external rotators; IRM – knee internal rotators; IR 25° – knee position in 25-degree shin internal rotation; IT – maximal isometric torque; PT – peak torque; SD – standard deviation; $\bar{\chi}$ – mean. Values in bold are statistically significant.

and external rotators in the operated leg in the ACLR group were significantly lower than those in the uninvolved leg, and significantly lower in the ACLR group than in the control group, at both angular velocities (Table 3).

Table 4 shows a deficit (percentage difference) between the parameters for extensor muscles of operated and the uninvolved legs, ranging from 21% to 30% under isometric conditions and from 11% to 50% under isokinetic conditions. The percentage difference in favor of the uninvolved leg was not as high for the knee flexors. In most of the participants, the difference between the 2 legs did not exceed 20% under isometric conditions or under isokinetic conditions. For most participants, the percentage difference of the IT and PT of muscles externally rotating the shin after ACLR did not exceed 20% and was slightly higher for the muscles internally rotating the shin. Nevertheless, there were also subjects who obtained results equal to or less than 10% difference between the operated and uninvolved limb (Table 4).

Discussion

The goal of postoperative therapies after ACLR is to restore strength and power, as reflected by the measurements of these parameters, in the muscles affecting the operated knee joints. The reduced torque produced by the muscles affecting the operated knee joint has a large effect on neuromuscular coordination and capacity of the joint.

In the present study, we used 2-plane biomechanical measurements under static and isokinetic conditions to monitor early effects of physiotherapy after ACLR. We found that a 17-week physiotherapy program for post-ACLR patients did not completely restore IT and PT for muscles affecting the operated knees in the sagittal and transverse planes in comparison to the contralateral limb, as reflected by the results of biomechanical testing. This suggests that postoperative treatment of longer duration is necessary for most patients. The highest statistically significant IT and PT values obtained in the sagittal plane from the operated knees were for extensor muscles, followed by flexor muscles, and then by the internal and external rotators of the shin in the transverse plane. Biomechanical analysis of these muscle groups, especially of the persistent deficit of PT and IT in the shin internal rotators, was especially important. In the ACLR group, ipsilateral grafts were harvested from the hamstring muscles, which are responsible for both flexion and internal rotation of the shin in the knee joint. This procedure probably caused the decrease in torque of the shin internal rotators. Another issue, which is outside the scope of this study, is the effect of semitendinosus and gracilis muscle tendons versus semitendinosus muscle tendon only, on the torque values of shin internal rotators. This problem was highlighted by Segawa et al. (2002), who studied male and female patients 12 months after ACLR [26].

Many of the studied patients after reconstruction of the anterior cruciate ligament were operated with the single-bundle method, but they did not constitute a significant

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

Table 4. Number of participants in the ACLR group and percent differences between the values obtained from the uninvolved leg and the operated leg.

Torque	Speed	Muscle group	Rotation	ACLR group (n)											
				Difference between the legs (%) In favor of the uninvolved leg						Difference between the legs (%) in favor of the operated leg					
				0–10	11–20	21–30	31–40	41–50	>50	0–10	11–20	21–30	31–40	41–50	>50
IT	0°/s	Q		2	6	11	5	4	1	0	0	1	0	0	0
		H		5	8	3	3	0	0	9	1	1	0	0	0
		IRM	ER30°	6	8	4	1	0	0	5	4	2	0	0	0
			IR25°	6	5	7	0	4	1	1	0	3	0	1	2
		ERM	ER30°	8	2	4	4	1	0	3	3	2	0	1	2
			IR25°	9	5	2	1	0	0	4	5	3	1	0	0
PT	60°/s	Q		1	5	7	8	4	3	1	1	0	0	0	0
		H		4	12	5	3	1	0	4	1	0	0	0	0
		IRM		15	6	5	0	0	1	1	2	0	0	0	0
		ERM		10	8	6	1	1	0	3	1	0	0	0	0
	180°/s	Q		1	8	7	6	5	2	0	1	0	0	0	0
		H		7	6	10	1	1	0	2	0	1	0	1	0
		IRM		10	8	2	1	1	0	6	2	0	0	0	0
		ERM		9	8	5	1	0	0	4	3	0	0	0	0

ACLR – anterior cruciate ligament reconstruction; ER 30° – knee position in 30-degree shin external rotation; ERM – muscles responsible for external rotation of the shin towards the thigh; H – knee flexors; IR 25° – knee position in 25-degree shin internal rotation; IRM – shin internal rotators; IT – maximal isometric torque; PT – peak torque; Q – knee extensors.

Table 5. Comparison of PT: IT ratio of flexor muscles rotating the shin in the knee joint to extensor muscles of the knee joint in both studied groups.

Ratio	Torque (angular velocity)	Control group				ACLR group			
		Dominant leg		Non-dominant leg		Operated leg		Uninvolved leg	
		$\bar{\chi}$	SD	$\bar{\chi}$	SD	$\bar{\chi}$	SD	$\bar{\chi}$	SD
H/Q	IT (0°/s)	0.48	0.12	0.46	0.15	0.50	0.12	0.40	0.11
	PT (60°/s)	0.60	0.08	0.61	0.10	0.71	0.16	0.57	0.09
	PT (180°/s)	0.58	0.10	0.59	0.08	0.69	0.14	0.56	0.09
IRM/Q	IT (0°/s)	0.16	0.03	0.16	0.03	0.22	0.06	0.17	0.03
	PT (60°/s)	0.18	0.04	0.19	0.04	0.23	0.05	0.18	0.04
	PT (180°/s)	0.20	0.04	0.21	0.04	0.27	0.06	0.20	0.04
ERM/Q	IT (0°/s)	0.14	0.04	0.14	0.04	0.19	0.05	0.14	0.03
	PT (60°/s)	0.18	0.03	0.18	0.04	0.22	0.04	0.17	0.03
	PT (180°/s)	0.21	0.03	0.20	0.04	0.26	0.05	0.20	0.04

ACLR – anterior cruciate ligament reconstruction; ERM – shin external rotators; H – knee flexors; IRM – shin internal rotators; IT – maximal isometric torque; PT – peak torque; Q – knee extensors; SD – standard deviation; $\bar{\chi}$ – mean. The presented IT for IRM was measured in 30-degree shin external rotation and the IT for ERM in 25-degree shin internal rotation.

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

majority. The ACL functionally consists of 2 distinct functional bundles – the anteromedial bundle and the posterolateral bundle [40] – therefore, an anatomic double-bundle ACLR is close to the native anatomy. Even though double-bundle reconstruction increases the rotational stability [41–44], the single-bundle ACLR is currently the most utilized method [42]. To date, there are no differences between the single-bundle and double-bundle ACL-reconstructed patients in terms of torques of muscles extending and flexing the knee joint [45], as well as muscles internally and externally rotating the shin [25]. For this reason, our study included patients with both types of reconstruction.

In humans, muscles are controlled by the nervous system during different kinds of locomotion [46]. Neuromuscular incoordination while performing dynamic movements with the lower limbs is believed to be the primary as well as a secondary cause of ACL injuries [47,48]. Moreover, persistently reduced strength in the knee-stabilizing musculature after ACLR and limitations in the normal function of the operated knee joint are predisposing factors for degenerative joint disease [49,50], a process that requires time [51,52]. Muscles support the passive apparatus of joints in maintaining stability and ensuring correct motion of the joints, limbs, and the entire body. Some muscle groups produce simple movements, such as knee extension. Reconstruction of the ACL and a minimum of 6 months of postoperative physical therapy allow patients to regain good neuromuscular coordination and to perform complex movements, such as flexion of the knee joint combined with shin rotation, and in changing directions while running [25].

Adequate biomechanical relationships of the muscle groups evaluated in the present study are responsible for maintaining balance for knee stability. Our results agree with previous reports on the relationship between torque and neuromuscular coordination [9,53].

The effect of muscular activity on the knee joint in the sagittal plane is the most frequently discussed issue in the literature. Parisaux et al. (2004) and Tashiro et al. (2003) showed significantly lower torque values in operated knee flexor muscles compared with the uninvolved knee between 11 and 24 months after ACLR [14,54]. Twelve months after ACLR, Urabe et al. (2002) found PT deficits in extensor muscles of the operated knee joint ranging from 8% to 12% compared with the uninvolved side [12]. Andrade et al. (2002) found 33% PT deficits in the same muscle group 8 months after ACLR [13]. Rebeyrotte et al. (2005) noted deficits ranging from 11.3% to over 15% for this group of muscles, depending on the applied angular velocity, at 2.5 years after ACLR [15]. Czamara (2008) showed complete restoration of IT values in extensor and flexor muscles of the operated knees compared with results obtained from the uninvolved legs and those obtained from the participants with no knee injuries, during the first 6 months following ACLR [37]. Czamara et al. (2011) revealed complete recovery of preoperative IT values under static conditions and preoperative PT of the flexor muscles during the first 6 months after ACLR, but some patients were found to have a 9% PT deficit in the extensor muscles of the operated knee compared with the uninvolved knee [36]. Morrisey et al. (2009) assessed the relationship between exercises with applied load in open kinematic chain and dislocation of the shin after injuries and ACLR surgical procedures [55]. Finally, Viola et al. (2000) and Armour et al. (2004) showed lower torque values in the muscles responsible for shin axial rotation in the operated knee joint than in the uninvolved side at 24–52 weeks after ACLR using grafts harvested from the semitendinosus and gracilis muscles [21,22].

Functional assessment of a muscle group requires not only quantitative assessment, but also qualitative analysis. The latter pertains to the relationships between different muscle groups of the same joint, symmetry in the groups of muscles affecting the knee joint, and comparison of the relationships between torque and joint angles between the operated and uninvolved limbs [36,56]. The present study performed additional analysis of the reciprocal proportions of IT and PT produced by the muscles affecting the knee joint, both in the sagittal and the transverse planes, in the group of male participants with no knee injuries. These values can be accepted as normative reference values. Analysis of the parameters in Table 5 indicate that the ratio of knee joint flexor to extensor muscles is about 0.50 in isometric conditions and about 0.60 in isokinetic conditions, which means that flexor muscles produced about half the IT and PT values of the extensor muscles. The ratio of shin internal rotators to knee extensors was 0.18 to 0.21, while the ratio of shin external rotators to knee extensors ranged from 0.14 to 0.21. In both cases, the torque values were about one-sixth those of the IT values produced by the knee joint extensors. Also of note is that each of these 2 separately analyzed groups of shin axial rotators produced IT values less than one-third of those produced by the knee flexors at a 30-degree angle in the sagittal plane (Tables 2, 3).

During week 17 after ACLR, a disturbed torque ratio was noted for most of the studied muscle groups (Table 5). However, analysis of the torque ratio for operated knees had limited diagnostic value when compared with the reference data obtained from the control group. For example, during week 17 after ACLR, the H/Q ratio of the operated limb was similar to that of the control group and higher than that of the uninvolved leg (Table 4). However, analysis of the actual differences in IT and PT values of the extensor muscles of the operated knee joint and those obtained from the control group revealed that the torque values of the extensor muscles in the operated knees were lower than those obtained from the uninvolved leg, and that the deficits ranged from 27% to 30%, respectively (Table 2).

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

Therefore, assessment of the ratios obtained must be corroborated by analysis of the actual torque values. Conversely, the assessment and analysis of the torque ratio in the control group provides an important reference value for the assessment of restored torque values in the studied muscle groups and their reciprocal relationships in ACLR patients.

The analysis of the percentage differences between the operated leg and the uninvolved leg (Table 4) showed that even though we can generally say which muscles groups have the largest deficits, each patient or athlete is different. For example, we can say that the percentage difference in the PT of muscles internally rotating the shin in the knee joint between 2 legs did not exceed 30% in most of the participants, but we cannot forget that there was 1 participant with a difference exceeding 50% (Table 4). Thus, physiotherapy should be individualized and based on objective assessment methods. It is also worth noting that the percentage difference was different for different muscle groups and measurement conditions, meaning that a comprehensive evaluation of knee muscles strength involves measurement of muscles acting in sagittal and transverse planes and under isometric and isokinetic conditions. It is also important that there were some patients whose torque values of the muscles affecting the operated knee joint were less than 10% smaller than in the uninvolved limb. There were also a few cases where the torques of muscles affecting the operated knee were even higher than in the uninvolved one, meaning that for some patients, 17 weeks of applied postoperative physiotherapeutic procedure after ACLR was sufficient to restore muscle strength of the operated knee joint to the level of the uninvolved one. These results confirm the assumption that strength recovery during physiotherapy is strongly individual and is affected not only by time since surgery, but also by many other issues [31].

Generally, our results suggest that even after 17 weeks of post-ACLR physiotherapy, most of athletes are not ready to return to sports. This means that the physiotherapy needs to be extended for a sport-specific period of time with elements like running, jumping, strength training under isokinetic conditions, and discipline-specific exercises [36]. The sport-specific elements should be wisely and gradually introduced and the trainer/physiotherapist should base the physiotherapy training on knowledge of graft healing and a comprehensive athlete evaluation. The results of this study also demonstrate the usefulness of dynamometers by physiotherapists in patient evaluation and training of biplanar muscle strength under both isometric and isokinetic conditions in monitoring and assessing the outcome of physiotherapy. ACL reconstruction itself affects the restoration of passive stability of the knee joint. One of the goals of postoperative rehabilitation is to restore the dynamic knee stability provided by the muscle groups affecting the operated limb. The measurements proposed allow monitoring of biomechanical strength and strength-speed characteristics of the muscles affecting the operated knee joint under maximal isometric tension and isokinetic conditions, which provides more information about the studied muscle groups under more natural conditions than can be achieved by performing single-plane isokinetic measurements. These tests and their interpretation can be used both for current assessment of postoperative therapeutic procedures and for remote assessment of the results of ACLR, and complement the comprehensive clinical assessment of an athlete's condition. Nevertheless, further studies involving strength measurement in more functional positions and in positions characteristic for knee injuries are needed.

Our study is limited by the relatively short observation period. Another limitation of this type of assessment is reducing it to the biomechanical assessment only. The measurements should be performed in connection with a comprehensive clinical evaluation, scales, and functional tests used in assessment of patients after ACLR and restoration of ROM, and then proprioception. Remote observation is also needed. Another limitation is the lack of a group of ACLR patients who underwent a physiotherapy protocol different from that of the participants in the present study.

Another limitation is the lack of the output data of the examined patients from the period before reconstruction. Nevertheless, it was impossible to take measurements of the muscles torques before the reconstruction was carried out, because most patients were operated on less than 3 months after injury to the ACL of the knee joint. Thus, an additional group of controls was created that included participants appropriately selected for the studied patients in terms of sex, body composition, and level of physical activity.

Conclusions

During 17-week postoperative physiotherapy after ACLR, persistent torque deficits were found in the studied muscle groups affecting the operated knee joints, both in the sagittal and the transverse planes. More than 70% of patients in the ACLR group needed to continue physiotherapy. It may be that the exercises were not sufficient to restore optimal strength in the tested muscle groups, and more research is needed to definitively determine if 17 weeks is sufficient to restore muscle strength. The present biplanar analysis of torque in the muscles affecting the knee joint under isometric and isokinetic conditions provides new information that should be more useful in evaluation of early effects of physiotherapy for patients after ACLR than are traditional uniplanar isokinetic measurements.

Conflict of interest

None.

References:

1. Busfield BT, Kharrazi FD, Starkey C et al: Performance outcomes of anterior cruciate ligament reconstruction in the National Basketball Association. Arthroscopy, 2009; 25(8): 825–30
2. Heijne A, Ang BO, Werner S: Predictive factors for 12-month outcome after anterior cruciate ligament reconstruction. Scand J Med Sci Sports, 2009; 19(6): 842–49
3. Risberg MA, Moksnes H, Storevold A et al: Rehabilitation after anterior cruciate ligament injury influences joint loading during walking but not hopping. Br J Sports Med, 2009; 43(6): 423–28
4. Eitzen I, Holm I, Risberg MA: Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. Br J Sports Med, 2009; 43(5): 371–76
5. Manske RC, Stovak M: Preoperative and postsurgical musculoskeletal examination of the knee, in postsurgical orthopedic sports rehabilitation knee & shoulder, R.C. Manske, Editor. Mosby Elsevier: St. Louis, Missouri, 2006; 31–53
6. Prodromos C, Brown C, FuF et al: The anterior cruciate ligament: Reconstruction and basic science. Philadelphia: Saunders, An Imprint of Elsevier, 2008
7. Myer GD, Schmitt LC, Brent JL et al: Utilization of modified NFL combine testing to identify functional deficits in athletes following ACL reconstruction. J Orthop Sports Phys Ther, 2011; 41(6): 377–87
8. Xergia SA, Pappas E, Zampeli F et al: Asymmetries in functional hop tests, lower extremity kinematics, and isokinetic strength persist 6 to 9 months following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther, 2013; 43(3): 154–62
9. Yosmaoglu HB, Baltaci G, Kaya D, Ozer H: Tracking ability, motor coordination, and functional determinants after anterior cruciate ligament reconstruction. J Sport Rehabil, 2011; 20(2): 207–18
10. Gao B, Cordova ML, Zheng NN: Three-dimensional joint kinematics of ACL-deficient and ACL-reconstructed knees during stair ascent and descent. Hum Mov Sci, 2012; 31(1): 222–35
11. Tsaklis P, Abatzides G: ACL rehabilitation program using a combined isokinetic and isotonic strengthening protocol. Isokinetics and Exercise Science, 2002; 10(4): 211–19
12. Urabe Y, Ochi M, Onari K: Changes in isokinetic muscle strength of the lower extremity in recreational athletes with anterior cruciate ligament reconstruction. Journal of Sport Rehabilitation, 2002; 11: 252–67
13. Andrade MS, Cohen S, Piçarro IC, Silva AC: Knee performance after anterior cruciate ligament reconstruction. Isokinetics and Exercise Science, 2002; 10(2): 81–86
14. Parisaux JM, Boileau P, Desnuelle C: [Isokinetic evaluation of the knee flexor muscles after anterior cruciate ligament reconstruction using gracilis and semitendinous tendon grafts]. Rev Chir Orthop Reparatrice Appar Mot, 2004; 90(1): 33–39 [in French]
15. Rebeyrotte-Boulegue I Daviet J-C, Oksman A, Mabit C: Isokinetic evaluation of anterior cruciate ligament reconstruction using a free fascia lata graft strengthened by gracilis tendon. Amsterdam, PAYS-BAS: IOS Press. 5, 2005
16. Bizzini M, Gorelick M, Munzinger U, Drobny T et al: Joint laxity and isokinetic thigh muscle strength characteristics after anterior cruciate ligament reconstruction: Bone patellar tendon bone versus quadrupled hamstring autografts. Clin J Sport Med, 2006; 16(1): 4–9
17. Ardern CL, Webster KE, Taylor NF, Feller JA: Hamstring strength recovery after hamstring tendon harvest for anterior cruciate ligament reconstruction: A comparison between graft types. Arthroscopy, 2010; 26(4): 462–69
18. Hsiao SF, Chou PH, Hsu HC, Lue YJ: Changes of muscle mechanics associated with anterior cruciate ligament deficiency and reconstruction. J Strength Cond Res, 2014; 28(2): 390–400
19. Knezevic OM, Mirkov DM, Kadija M et al: Evaluation of isokinetic and isometric strength measures for monitoring muscle function recovery after anterior cruciate ligament reconstruction. J Strength Cond Res, 2014; 28(6): 1722–31
20. Larsen JB, Farup J, Lind M, Dalgas U: Muscle strength and functional performance is markedly impaired at the recommended time point for sport return after anterior cruciate ligament reconstruction in recreational athletes. Hum Mov Sci, 2015; 39: 73–87
21. Viola RW, Sterett WI, Newfield D et al: Internal and external tibial rotation strength after anterior cruciate ligament reconstruction using ipsilateral semitendinosus and gracilis tendon autografts. Am J Sports Med, 2000; 28(4): 552–55
22. Armour T, Forwell L, Litchfield R et al: Isokinetic evaluation of internal/external tibial rotation strength after the use of hamstring tendons for anterior cruciate ligament reconstruction. Am J Sports Med, 2004; 32(7): 1639–43
23. Czamara A, Szuba Ł, Krzemińska A et al: Effect of physiotherapy on the strength of tibial internal rotator muscles in males after anterior cruciate ligament reconstruction (ACLR). Med Sci Monit, 2011; 17(9): CR523–31
24. Hrycyna M, Zielinski J: Torque of the shank rotating muscles in patients with knee joint injuries. Acta Bioeng Biomech, 2011; 13(4): 77–83
25. Czamara A, Królikowska A, Szuba Ł et al: Single- versus double-bundle anterior cruciate ligament reconstruction: A new aspect of knee assessment during activities involving dynamic knee rotation. J Strength Cond Res, 2015; 29(2): 489–99
26. Segawa H, Omori G, Koga Y et al: Rotational muscle strength of the limb after anterior cruciate ligament reconstruction using semitendinosus and gracilis tendon. Arthroscopy, 2002; 18(2): 177–82
27. Meyer EG, Haut RC: Anterior cruciate ligament injury induced by internal tibial torsion or tibiofemoral compression. J Biomech, 2008; 41(16): 3377–83
28. Shimokochi Y, Shultz SJ: Mechanisms of noncontact anterior cruciate ligament injury. J Athl Train, 2008; 43(4): 396–408
29. Mather RC 3rd, Koenig L, Kocher MS et al: Societal and economic impact of anterior cruciate ligament tears. 2013; 95: 1751–59
30. Walden M, Hagglund M, Ekstrand J: High risk of new knee injury in elite footballers with previous anterior cruciate ligament injury. Br J Sports Med, 2006; 40(2): 158–62; discussion 158–62
31. Kruse LM, Gray B, Wright RW: Rehabilitation after anterior cruciate ligament reconstruction: A systematic review. J Bone Joint Surg Am, 2012; 94(19): 1737–48
32. Saka T: Principles of postoperative anterior cruciate ligament rehabilitation. World J Orthop, 2014; 5(4): 450–59
33. Wright RW, Haas AK, Anderson J et al: Anterior cruciate ligament reconstruction rehabilitation: MOON guidelines. Sports Health, 2015; 7(3): 239–43
34. Zatsiorsky V, Kreamer W: Krafttraining in praxis und wissenschaft. Aachen: Meyer & Meyer Verlag, 2008 [in German]
35. Tegner Y, Lysholm J: Rating systems in the evaluation of knee ligament injuries. Clin Orthop Relat Res, 1985; (198): 43–49
36. Czamara A, Tomaszewski W, Bober T, Lubarski B: The effect of physiotherapy on knee joint extensor and flexor muscle strength after anterior cruciate ligament reconstruction using hamstring tendon. Med Sci Monit, 2011; 17(1): CR35–41
37. Czamara A: Moments of muscular strength of knee joint extensors and flexors during physiotherapeutic procedures following anterior cruciate ligament reconstruction in males. Acta Bioeng Biomech, 2008; 10(3): 37–44
38. Jaric S, Radosavljevic-Jaric S, Johansson H: Muscle force and muscle torque in humans require different methods when adjusting for differences in body size. Eur J Appl Physiol, 2002; 87(3): 304–7
39. Royston P: Remark AS R94: A remark on algorithm AS 181: The W-test for normality. Journal of the Royal Statistical Society. Series C (Applied Statistics), 1995; 44(4): 547–51
40. Girgis FG, Marshall JL, Monajem A: The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res, 1975; (106): 216–31
41. Björnsson H, Desai N, Musahl V et al: Is double-bundle anterior cruciate ligament reconstruction superior to single-bundle? A comprehensive systematic review. Knee Surg Sports Traumatol Arthrosc, 2015; 23(3): 696–739
42. Tiamklang T, Sumanont S, Foocharoen T, Laopaiboon M: Double-bundle versus single-bundle reconstruction for anterior cruciate ligament rupture in adults. Cochrane Database Syst Rev, 2012; 11: Cd008413
43. van Eck CF, Kopf S, Irrgang JJ et al: Single-bundle versus double-bundle reconstruction for anterior cruciate ligament rupture: A meta-analysis – does anatomy matter? Arthroscopy, 2012; 28(3): 405–24
44. Zelle BA, Vidal AF, Brucker PU, Fu FH: Double-bundle reconstruction of the anterior cruciate ligament: anatomic and biomechanical rationale. J Am Acad Orthop Surg, 2007; 15(2): 87–96

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]

45. Ha J-K, Lee DW, Kim JG: Single-bundle versus double-bundle anterior cruciate ligament reconstruction: A comparative study with propensity score matching. Indian J Orthop, 2016; 50(5): 505–11
46. Vallis LA, Reed-Jones RJ: Modifications to Central Motor Control Strategies Following Anterior Cruciate Ligament Injury. A New Direction for ACL Research, in Anterior Cruciate Ligament (ACL): Causes of Injury, Adverse Effects, and Treatment Options, Yeager CR (ed.), editor. Nova Science Publishers, 2010; 141–55
47. Hewett TE, Myer GD, Ford KR et al: Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. Am J Sports Med, 2005; 33(4p. 492–501
48. Zazulak BT, Hewett TE, Reeves NP et al: Deficits in neuromuscular control of the trunk predict knee injury risk: A prospective biomechanical-epidemiologic study. Am J Sports Med, 2007; 35(7): 1123–30
49. Slemenda C, Heilman DK, Brandt KD et al: Reduced quadriceps strength relative to body weight: A risk factor for knee osteoarthritis in women? Arthritis Rheum, 1998; 41(11): 1951–59
50. Thorstensson CA, Petersson IF, Jacobsson LT et al: Reduced functional performance in the lower extremity predicted radiographic knee osteoarthritis five years later. Ann Rheum Dis, 2004; 63(4): 402–7
51. Hootman JM, Albohm MJ: Anterior cruciate ligament injury prevention and primary prevention of knee osteoarthritis. J Athl Train, 2012; 47(5): 589–90
52. Pinczewski LA, Lyman J, Salmon LJ et al: A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: A controlled, prospective trial. Am J Sports Med, 2007; 35(4): 564–74
53. Tagesson S: Dynamic knee stability after anterior cruciate ligament injury. Emphasis on rehabilitation, in Department of Medical and Health Sciences. Linköping University: Linköping, 2008
54. Tashiro T, Kurosawa H, Kawakami A et al: Influence of medial hamstring tendon harvest on knee flexor strength after anterior cruciate ligament reconstruction. A detailed evaluation with comparison of single- and double-tendon harvest. Am J Sports Med, 2003; 31(4): 522–29
55. Morrissey MC, Perry MC, King JB: Is knee laxity change after ACL injury and surgery related to open kinetic chain knee extensor training load? Am J Phys Med Rehabil, 2009; 88(5): 369–75
56. Staniszewski M, Mastalerz A, Urbanik C: The influence of a four-week training on an inclined plane on the isokinetic knee power. Acta of Bioengineering and Biomechanics, 2006; 8(2): 51–58

Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]