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TITLE

Asymmetrical lower extremity loading early after ACL reconstruction is a significant predictor of asymmetrical loading at the time of return to sport

AUTHORS

Luciana Labanca[1], Luca Laudani[1], Federica Menotti[1], Jacopo Rocchi[1,2], Pier Paolo Mariani[1,2], Arrigo Giombini[3], Fabio Pigozzi[1,2], Andrea Macaluso[1,2 *]

AFFILIATIONS

[1] Department of Movement, Human and Health Sciences, University of Rome Foro Italico, Rome, Italy

[2] Villa Stuart Sport Clinic-FIFA Medical Center of Excellence, Rome, Italy

[3] Department of Medicine and Health Sciences, University of Molise, Campobasso, Italy

***** Corresponding Author:

Andrea Macaluso, MD PhD

Department of Movement, Human and Health Sciences

University of Rome Foro Italico

Piazza Lauro De Bosis 6, 00135, Roma, Italy

Phone: +39 06 36 733 242, Fax: +39 06 36 733 214, e-mail: andrea.macaluso@uniroma4.it

Asymmetrical lower extremity loading early after ACL reconstruction is a significant predictor of asymmetrical loading at the time of return to sport

ABSTRACT

Objectives: To examine whether asymmetrical lower limb loading early after ACL reconstruction (one month) can predict asymmetrical lower limb loading at the time of return to sport (6 months) and whether other early predictors as knee joint range of motion or maximal isometric strength affect this relationship.

Design: Ground reaction forces were measured during a sit to stand task (STS) one month after ACL reconstruction and a vertical countermovement jump (CMJ) 6 months after ACL reconstruction in 58 athletes. Other early post-operative measurements were knee joint range of motion (2 weeks, 1 month and 2 months after surgery) and maximal isometric strength of the knee extensor and flexor muscles (2 months after surgery). Linear regression models were developed using side-to-side limb symmetry index (LSI) of CMJ as the dependent variable.

Results: LSI of STS 1 month after surgery was a significant independent predictor of LSI of CMJ 6 months after surgery. After accounting for deficits in knee joint range of motion and LSI of maximal isometric strength ($\Delta R^2=0.35$ $p<0.01$), LSI of STS predicted LSI of CMJ ($\Delta R^2=0.14$ $p<0.01$).

Conclusions: Asymmetrical lower extremity loading one month after ACL reconstruction is an early predictor of asymmetrical lower extremity loading 6 months after surgery.

Key Words: *knee, rehabilitation, sit to stand, vertical jump*

INTRODUCTION

Asymmetrical lower extremity loading has been reported following reconstruction of the anterior cruciate ligament (ACL) during all rehabilitation phases in a number of functional tasks such as chair rising[1], squatting[2], stair climbing[3], jumping[4] and jump-landing.[5] It has been shown that, in most cases, athletes exhibit asymmetry also when returning to sport activities and, in some cases, for years after surgery. [2, 4] Return to sport with lower limb asymmetrical loading may lead to deleterious consequences both in the short term, such as an increase of the risk for re-injury[6], and in the long term, such as the development of knee post-traumatic osteoarthritis.[7]

Asymmetrical lower extremity loading can easily be assessed in advanced phases of rehabilitation, by using tasks which resemble sport performance like a vertical jump on force platforms[4,8]. However, testing asymmetrical lower extremity loading during functional movements in the early phases after surgery is an issue, as these movements must not excessively overload the knee joint. Chmielewski et al.[9] have proposed a sit-to-stand (STS) movement on a one force platform early after ACL reconstruction to identify abnormalities in lower limb extremity loading during the rising phase of the movement. It does not distinguish between the involved and uninvolved limb. Laudani et al.[1], therefore, have adopted a STS movement performed on two force platforms to separately measure the contribution of the involved and uninvolved limb and to quantify the limb symmetry index (LSI = [surgical side/nonsurgical side] × 100) as a clinical measure of asymmetry in peak force on the affected limb.

The question arises as to whether an early assessment of asymmetrical lower extremity loading (such as the LSI of peak force during a STS carried out one month after surgery) is a predictor of a late assessment of asymmetrical lower extremity loading (such as the LSI of peak force during a vertical countermovement jump (CMJ)), which has been shown to be a useful functional measure of asymmetrical loading in advanced phases after surgery.[4,8] The vertical jump on a force platform for the late assessment of asymmetrical lower extremity loading is related to sport performance.[10,11] It is not surprising that it has been used since the late sixties as the gold standard for assessing maximal muscle power in the lower limbs.[12] The STS on two force platforms for the early assessment of LSI has been recently introduced and proved to be a valid test to quantify functional deficits, their changes over time and between groups. [1] Other early assessments in the early phases after ACL reconstruction, which may affect lower extremity loading symmetry, include knee joint range of motion[13] and knee extensor and flexor muscles strength.[9,14]

The aim of this study, therefore, was to investigate the relationship between asymmetrical lower extremity loading one month after ACL reconstruction measured by means of a STS movement and asymmetrical lower extremity loading six months after surgery measured by means of a CMJ. Six months is often reported as the time for return to sports.[15] We hypothesized that LSI of STS may predict LSI of CMJ even after accounting for deficits in knee joint range of motion and LSI of maximal isometric strength, which are other early determinants for the recovery of lower extremity loading symmetry.

METHODS

Participants

The study was carried out on 58 patients, 53 men and 5 women (age: 22±6 years; stature: 1.79±0.06 m; mass: 73.4±7.9 kg), who underwent unilateral isolated ACL reconstruction at Villa Stuart Sports Clinic, FIFA Medical Center of Excellence, in Rome. Inclusion criteria were: a) participation in competitive sport activities (Tegner level scale[16] of 9-10 before ACL injury), b) same standardized postoperative rehabilitation protocol; c) return to previous activity level 6 months after surgery. Exclusion criteria were: a) concomitant injury to any other knee ligament, b) associated meniscal tear, c) history of previous surgery on either knee, d) postoperative presence of joint swelling at 15 days. All patients underwent arthroscopic reconstruction with ipsilateral autologous bone-patellar tendon-bone graft, which was performed by only one surgeon. None of the patients followed any preoperative rehabilitative protocols. A standardized postoperative rehabilitation protocol was administrated at the same center under supervision of physical therapists 5 days/week. Briefly, all patients were asked to wear a post-operative immobilizer immediately after surgery and to bear weight on the second day. During the first 2 weeks, the rehabilitation program consisted of continuous passive mobilizations, together with neuromuscular electrical stimulations of the quadriceps, hamstrings and calf muscles, and isometric straight leg rises, which were carried out until the end of the first month. Squatting exercises were incorporated within the first 3-4 weeks. During the second and third month, strengthening exercises and hydrokinetic therapy were implemented. Exercises in water involved cycling, walking and stepping movements.

An eligibility investigation was initially conducted on a cohort of 120 athletes undergoing ACL reconstruction. Forty-two patients were excluded due to story of previous ACL injury and concomitant meniscus or other knee ligaments injury. Nine of the 78 remaining patients decided to drop-out of the study. Seven patients were not able to perform the testing sessions because of knee joint swelling, effusion and patellar tendinopathy. Four patients were excluded as they followed a rehabilitation program elsewhere. Fifty-eight patients, therefore, completed all testing sessions (Figure 1).

With approval of the Ethics Committee of the University of Rome La Sapienza, the study was carried out in accordance with the Declaration of Helsinki, and informed consent was obtained from all participants.

Procedures

Collection of demographic data (age, gender, body mass, height) and Tegner activity level before injury was completed during the first visit to the laboratory. Participants were scheduled for 4 follow-up visits at the laboratory two weeks, one month, two months and six months after surgery.

Sit-to-stand testing

STS testing was carried out one month after surgery. The STS task consisted of rising from a seat as fast as possible. The height of the seat was adjusted to the shank length to obtain a 90-degrees angle at the knee joint. The participants were asked to keep their trunk in a vertical position, their arms held across their chest, and their feet shoulder-width apart. In addition, they were asked to focus on a target, which was set at eye level and located 3 m away, to preserve head stability and balance control throughout the movement. Once the correct sitting posture was obtained, the participants were verbally instructed to stand up as fast as possible and maintain a still upright position for a minimum of 5 s. A total of three STS trials with 1-min rest in between were performed for each session. Ground reaction forces during the STS were measured by means of 2 six-component force platforms (KISTLER, model 9281 B; Winterthur, Switzerland; 100-Hz sampling frequency), which were positioned one below each foot. The vertical component of the ground reaction force was offline filtered using a digital, low-pass, second-order, Butterworth filter with a cutoff frequency set at 15 Hz. Each STS task was divided into a preparation phase and a rising phase as in Laudani et al.[1]. Total duration of the STS transfer was calculated as the time interval between the start and end points, with the shortest of the three trials selected for further analysis. Peak values of the vertical components of ground reaction force of the seat-off instant were calculated for both limbs and used for further analysis (Figure 2).

Countermovement jump testing

CMJ testing was performed six months after surgery. Subjects were asked to stand in an upright position with their hands on their hips[17]. They were then asked to quickly squat with knees flexes to approximately 90 degrees and then jump immediately as high as possible without pausing. A total of three CMJ trials with 1-min rest in between were performed for each session. Ground reaction forces during CMJ were measured by means of 2 six-component force platforms (KISTLER, model 9281 B; Winterthur, Switzerland; 100-Hz sampling frequency), which were positioned one below each foot (Figure 3). The vertical component of the ground reaction force was offline filtered using a digital, low-pass, second-order, Butterworth filter with a cutoff frequency set at 15 Hz. Total duration of the CMJ was calculated as the time interval between the start and take-off points, with the shortest of the three trials selected for further analysis. Peak values of the vertical components of ground reaction forces were identified during the concentric phase of each jump and used for further analysis.

Range of motion of the knee joint

Passive range of motion (ROM) of the knee joint was measured two weeks, one month and two months after surgery by means of a universal manual goniometer with the patient in a supine position[18]. The International Knee Documentation Committee Form[19] was used to classify the difference in knee extension and knee flexion between the ACL reconstruction knee and the contralateral healthy one with a 1 to 4 score. Knee extension deficits (EXTd) were recorded as 1 < 3°, 2 = 3-5°, 3 = 6-10° and 4 > 10°. Knee flexion deficits (FLEXd) were recorded as 1 < 5°, 2 = 6-15°, 3 = 16-25° and 4 > 25°.

Strength testing

Strength testing was carried out in all patients two months after surgery. Each patient warmed up on an exercise bicycle for 5 min at a low resistance before performing the strength test. All participants were tested for isometric maximal voluntary contraction (MVC) of the knee extensor muscles at a 30 (MVCe30) and 90° (MVCe90) joint angle and of the knee flexor muscles at a 90°(MVCf90) joint angle in both limbs in random order. During the test, participants were seated comfortably on a leg-extension machine (Technogym, Forli-Cesena, Italy) for knee extension MVC and on a leg-curl machine (Technogym, Forli-Cesena, Italy) for knee flexion MVC. Patients were positioned with their trunk erect and fastened by three crossing belts on both machines. Muscle force was recorded using a load cell connected to a computerized system unit (MuscleLab, Bosco-System Technologies, Rieti, Italy). The MVC task consisted of an increase to a maximum in the force exerted by the leg muscles.[20] Participants were able to follow their performance on the computer screen and were verbally encouraged to achieve a maximum and to maintain it for at least 2 s before relaxing. A target line was always set on the computer screen at a value 20% higher than the best performance. MVC was calculated as the largest 1-s average reached within any single force recording. For each test (30° and 90° extension MVC and 90° flexion MVC), a minimum of 3 attempts were performed with 3 min intervals, and the one with the highest force value was chosen as MVC. Participants were asked to make a further attempt if the MVC of their last trial exceeded that of previous trials.[21]

Data analysis and statistics

Descriptive statistics were used to summarize demographic data. Side to side symmetry was quantified for all isometric MVCs performed, STS and CMJ using the Limb Symmetry Index (LSI), which was calculated as the ratio between the involved and uninvolved limb expressed as a percentage. ROM of the knee joint was registered according to the IKDC Form using a 1 to 4 score. Correlation analysis was conducted to explore relationships between variables and only those significantly correlated with LSI of CMJ six months post-surgery (Table 1) were used for further regression analysis. First, a linear regression analysis with LSI of CMJ as the dependent variable was conducted to find out the predictive value of LSI of STS. Then in order to determine if LSI during STS one month after surgery could predict LSI of CMJ after accounting for other early predictors, hierarchical linear regression models were developed using LSI of CMJ six month after ACL reconstruction as the dependent variable. The first step of the regression included

LSI ofMVCe90° knee flexion and IKDC scores of EXTd two weeks, one month and two months after surgery. In the second step, LSI of STS one month after ACL reconstruction was entered to investigate its predictive value above and beyond the other considered variables. A significance level of $p<0.05$ was adopted. All statistical analyses were performed using SPSS version 20.0 (SPSS, Inc., Chicago, IL - IBM, Somers, NY, USA).

RESULTS

Descriptive statistics

Mean values of LSI of STS and CMJ were 62%±14% and 85%±10%, respectively. Mean values of LSI of MVCe30, MVCe90 and MVCf90 were 67%±23%, 56%±26% and 78%±19%, respectively. Two weeks after surgery IKDC score for EXTd was 1 in 56% of the patients, 2 in 29%, and 3 in 15%. IKDC scores for EXTd and FLEXd two weeks, one month and two months after surgery are shown in Table 1.

Correlations between variables

Results of correlation analysis are shown in Table 2. LSI of CMJ was significantly and positively correlated with LSI of MVC of the knee extensor muscles at 90°knee flexion. A significantly negative correlation was found between LSI of CMJ and knee extension deficits at two weeks, one month and two months after surgery. No significant correlations were found between LSI of CMJ and LSI of MVC of the knee extensor muscles at 30° knee flexion, LSI of MVC of the knee flexor muscles and knee flexion deficit.

Linear regression models

LSI of STS one month after surgery significantly predicted LSI of CMJ six months after surgery. The linear regression summary conducted to investigate the predictive value of STS is displayed in Table 3.

Table 4 illustrates the hierarchical multiple regression models that were conducted to assess whether LSI of STS one month after ACL reconstruction predicts LSI of CMJ six months after surgery, after accounting for the variance explained by LSI of isometric MVC of knee extensor muscle at 90° knee flexion and IKDC scores for knee extension deficit two weeks, one month and two months after surgery. Model 1 of the regression was significantly predictive of LSI of CMJ by explaining 35% of the variance. IKDC score for knee extension deficit two weeks after surgery (β=-0.31, $p<0.05$) and LSI of knee extensor MVC (β=0.27, $p<0.05$) gave a significant contribution to the model. The addition of LSI of STS to previous variables significantly explained additional variance ($\Delta R^2 = 0.14$, $p<0.001$) for LSI of CMJ prediction. However the unique contribution of each variable was no longer significant when LSI of STS was entered into the Model 2. LSI of STS (β=0.42, $p<0.05$) was the only significant variable in Model 2.

DISCUSSION

The main result of this study was that LSI of STS 1 month after surgery significantly predicted LSI of CMJ 6 months after surgery, both independently and after accounting for deficits in knee joint range of motion and LSI of maximal isometric strength. This result suggests that the recovery of symmetry in lower extremity loading during the first month after surgery may affect the subsequent functional recovery up to return to sport, which could have important practical applications for designing and monitoring early interventions.

LSI of peak force during STS 1 month after surgery was 62%, which is consistent with the findings of Laudani et al.[1] LSI of peak force during CMJ at 6 months was 85%. To the best of the authors' knowledge, this is the first study reporting asymmetrical lower extremity loading during a countermovement jump on two force platforms 6 months after ACL reconstruction. Previous studies have suggested an inter-limb symmetry ranging from 85%[22] to 90%[23], but these reference values referred to single-legged jumping tasks, which are commonly used in a clinical setting, thus making comparisons difficult.

The major advantage in assessing asymmetrical lower extremity loading by adopting a task requiring simultaneous loading of the lower limbs, rather than single-legged tasks, is that bilateral movements occur in most activities of daily living or sport practice. It has been shown that postural control is impaired early after ACL reconstruction[24] and postural adaptations occur quickly, as the central nervous system responds with new motor control strategies by transferring load from the injured limb to the uninvolved limb.[2,25,26] In the present study, an early assessment of asymmetrical lower extremity loading, by means of a STS on two force platforms, which was carried out one month after surgery, was predictive of a late assessment of asymmetrical lower extremity loading, by means of a CMJ on two force platforms, which was carried out 6 months after surgery. Therefore, the early postural adaptations leading to asymmetrical loading in the lower extremity may persist over time. Current rehabilitation programs, which are mostly based on strengthening exercises for the operated limb, may be ineffective against asymmetrical loading. Perhaps, specific programs should be designed to address this issue by introducing double limb exercises in the early phase of rehabilitation, which focus on maintenance of symmetry, thus addressing motor control more than strengthening. In addition, cut-off scores should be identified for determining what levels of lower limb asymmetry loading are necessary to progress between stages of rehabilitation.

LSI of maximal isometric strength of both the knee flexor and extensor muscles, together with deficits in ROM of the knee joint were accounted for as other possible early predictors of asymmetrical lower extremity loading in the hierarchical linear regression models, due to their important role for lower extremity loading symmetry and functional recovery following knee surgery.[9,27, 28] Asymmetry in knee extensor muscle strength and knee extension deficits in ROM were both predictive of asymmetrical loading during CMJ six months after ACL reconstruction. However, the most significant predictor was asymmetrical loading during STS one month after surgery. This may be attributed to the fact that STS and CMJ are both functional and dynamic movements.

Some limitations need to be addressed in the present study. First of all, results of this study can be considered representative only for populations of athletes. Further investigations are needed to explore the predictive value of early assessments of asymmetrical lower extremity loading also for sedentary and non competitive individuals. A further limitation of the study is that other early factors that may affect asymmetrical lower extremity loading should be taken into account, such as psychological factors and other concomitant injuries to the knee joint.[29] Lastly, using LSI in research and clinical practice for rehabilitation has been frequently questioned as it may conceal results of physical performance, in particular during long-term observational studies.[30] It has been argued that asymmetry alone cannot be used to understand which of the two limbs has improved or worsened. However, while this limitation applies to single-legged tasks, it may not be relevant to double-legged functional movements looking at how load was managed between the two limbs.

In conclusion, asymmetrical lower extremity loading one month after ACL reconstruction is a significant predictor of asymmetrical loading six months after surgery when return to sport is often suggested, which could have important practical applications for designing and monitoring early interventions. Further studies should explore whether specific training programs may be effective for contrasting asymmetrical lower extremity loading after ACL surgery. In addition, cut-off points for asymmetrical lower extremity loading should be identified for progression from one phase of rehabilitation to the next.

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FIGURE LEGENDS

Figure 1. Flow-chart showing patients recruited for the study.

Figure 2. Vertical components of ground reaction forces during the STS in both the involved and uninvolved limb in a representative participant one month after ACL reconstruction.

Figure 3. Countermovement jump performed on two force platforms.

Figure 1

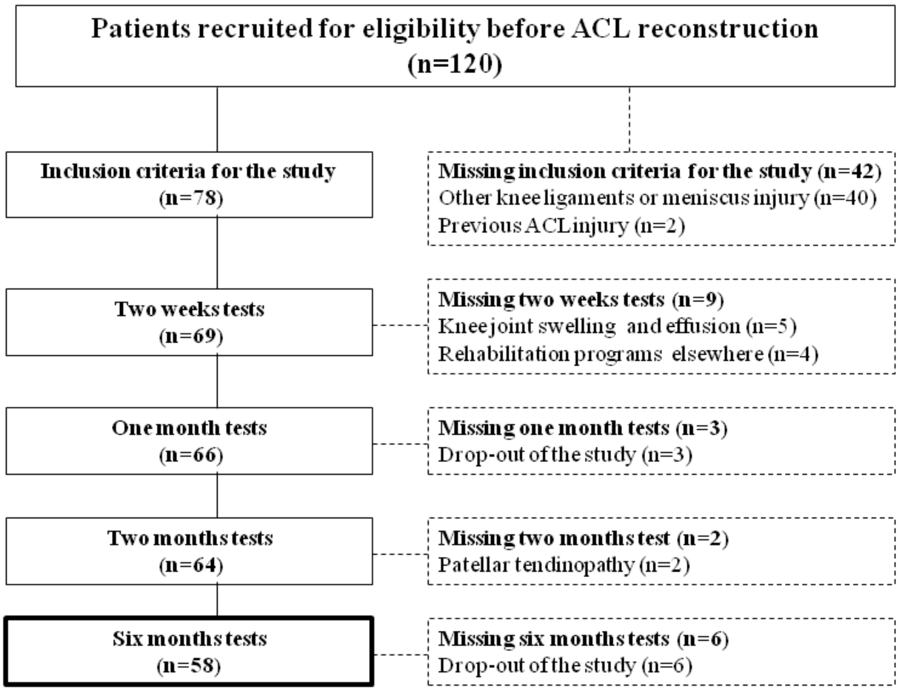
Patients recruited for eligibility before ACL reconstruction (n=120)
Inclusion criteria for the study (n=78)
Missing inclusion criteria for the study (n=42)
Other knee ligaments or meniscus injury (n=40)
Previous ACL injury (n=2)
Two weeks tests (n=69)
Missing two weeks tests (n=9)
Knee joint swelling and effusion (n=5)
Rehabilitation programs elsewhere (n=4)
One month tests (n=66)
Missing one month tests (n=3)
Drop-out of the study (n=3)
Two months tests (n=64)
Missing two months test (n=2)
Patellar tendinopathy (n=2)
Six months tests (n=58)
Missing six months tests (n=6)
Drop-out of the study (n=6)

Figure 2

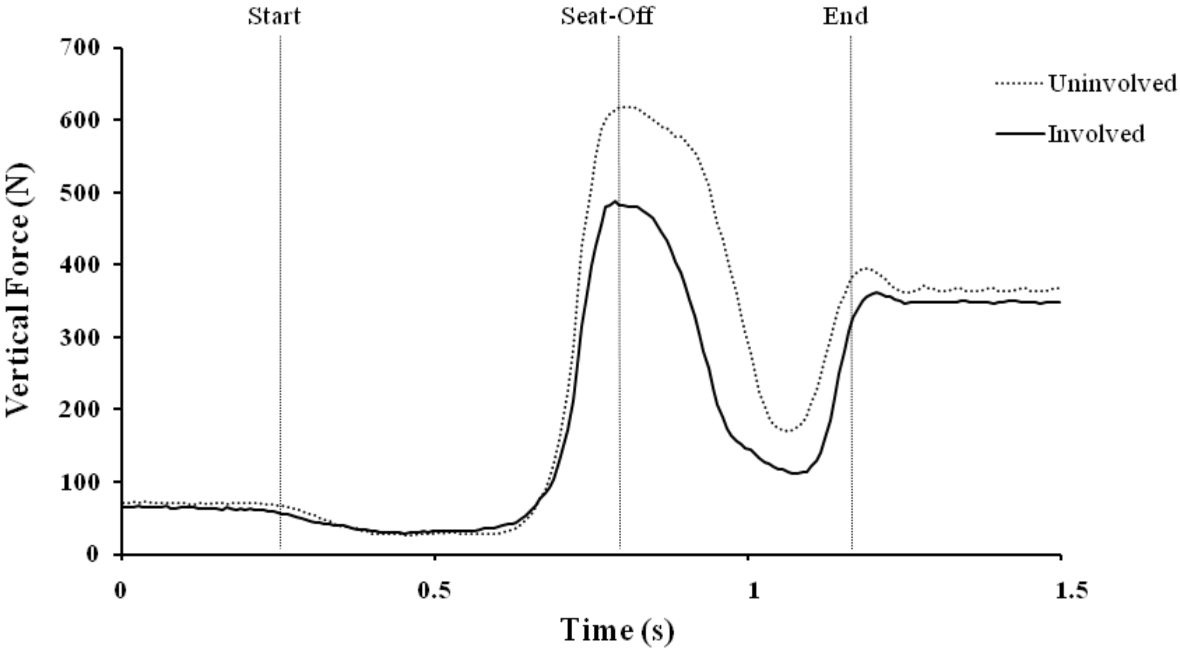
Start
Seat-Off
End
700
600
500
400
300
200
100
0
Vertical Force (N)
Uninvolved
Involved
0
0.5
1
1.5
Time (s)

Figure 3

TABLES

Table1. Descriptive statistics of IKDC scores for knee extension and flexion deficits two weeks, one month and two months after ACL reconstruction.

		Two weeks	One month	Two months
EXTd				
	1	56%	58%	86%
	2	29%	30%	14%
	3	15%	11%	0
	4	0	2%	0
FLEXd				
	1	4%	33%	84%
	2	2%	33%	12%
	3	4%	14%	4%
	4	90%	19%	0

Knee extension deficits (EXTd): 1 < 3°, 2 = 3-5°, 3 = 6-10°, 4 > 10°.

Knee flexion deficits (FLEXd): 1 < 5°, 2 = 6-15°,3 = 16-25°, 4 > 25°.

Table 2. Spearman's correlation between Limb Symmetry Index of CMJ 6 months after ACL reconstruction and post-operative factors.

	CMJ (6 months)	
	R	*P*
EXTd (2 weeks)	-0.36*	0.01
FLEXd (2 weeks)	-0.25	0.09
EXTd (1 month)	-0.27*	0.04
FLEXd (1 month)	-0.18	0.17
EXTd (2 months)	-0.33*	0.01
FLEXd (2 months)	-0.05	0.69
STS (1 month)	0.32*	0.02
MVCe30° (2 months)	0.22	0.10
MVCe90° (2 months)	0.38**	0.006
MVCf90° (2 months)	0.18	0.18

* $p < 0.05$, **$p < 0.01$, $p < 0.001$***

r Spearman's correlation coefficient

CMJ, vertical countermovement jump; EXTd, extension deficit of the knee joint; FLEXd, flexion deficit of the knee joint; STS, sit to stand; MVCe30°, maximal voluntary contraction of knee extensor muscles at 30 degrees of knee flexion; MVCe90°, maximal voluntary contraction of knee extensor muscles at 90 degrees of knee flexion; MVCf90°, maximal voluntary contraction of knee flexor muscles at 90 degrees of knee flexion.

Table 3. Linear regression summary**.**

	CMJ		
	R	**R^2**	**F**
STS	0.48	0.23	14,8***

** $p < 0.05$, **$p < 0.01$, $p < 0.001$****

CMJ, countermovement jump; STS, sit to stand.

Table 4. Hierarchical multiple regression analysis examining the predictive value of early asymmetrical lower extremity loading measured by means of a STS after accounting for the variance explained by knee extension deficit and knee extensor muscles strength.

	B	***SE***	***Β***	***t***	R^2	ΔR^2	***F***
Model 1					0.35	0.35	5.46**
EXTd (2weeks)	-4.42	1.98	-0.31	-2.22*			
EXTd (1month)	-1.40	2.11	-0.10	-0.66			
EXTd (2months)	-7.75	4.13	-0.25	-1.87			
MVCe90° (2 months)	0.10	0.05	0.27	2.04*			
Model 2					0.49	0.14	7.69***
EXTd (2weeks)	-1.75	1.94	-0.12	-0.90			
EXTd (1month)	-3.40	1.98	-0.24	-1.72			
EXTd (2months)	-6.32	3.72	-0.21	-1.69			
MVCe90° (2 months)	0.08	0.04	0.21	1.78			
STS (1 month)	0.32	0.09	0.42	3.32*			

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

EXTd, extension deficit of the knee joint; MVCe90°, maximal voluntary contraction of knee extensor muscles at 90 degrees of knee flexion; STS, sit to stand.