A Countermovement Jump for the Midterm Assessment of Force and Power Exertion After Anterior Cruciate Ligament Reconstruction

Luciana Labanca, PhD, Francesco Budini, PhD, Ludovica Cardinali, MSc, Giulia Concilio, MSc, Jacopo Emanuele Rocchi, PhD, Pier Paolo Mariani, MD, Luca Laudani, PhD, and Andrea Macaluso, MD, PhD

Objective: The aim of this study was to assess force and power exertion during a countermovement jump after anterior cruciate ligament reconstruction using either semitendinosus and gracilis or bone-patellar tendon-bone graft.

Design: One hundred-nineteen semitendinosus and gracilis and 146 bone-patellar tendon-bone participants performed a countermovement jump on two force platforms after 3 (T1) and 6–9 mos (T2) from surgery. Twenty-four healthy participants served as control group. Peak force of eccentric and concentric phases and peak power were obtained from the analysis of vertical components of the ground reaction forces. Asymmetry was quantified by means of limb symmetry index.

Results: Eccentric peak force was significantly ($P < 0.05$) lower than concentric peak force in both bone-patellar tendon-bone and semitendinosus and gracilis at T1 and T2. At T1, bone-patellar tendon-bone showed higher peak power, but lower limb symmetry index in eccentric and concentric compared with semitendinosus and gracilis. At T2, bone-patellar tendon-bone showed higher peak power than semitendinosus and gracilis, although there were no differences in limb symmetry index between the two groups, which however was significantly ($P < 0.05$) lower in both groups when compared with control group.

Conclusions: Bone-patellar tendon-bone and semitendinosus and gracilis participants showed asymmetries in eccentric and concentric force during a countermovement jump. Bone-patellar tendon-bone showed greater asymmetries and a higher peak power respect to semitendinosus and gracilis participants.

Key Words: Semitendinosus, Bone-Patellar Tendon-Bone, Eccentric, Power, Rehabilitation, Symmetry

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What Is Known

- Individuals with an anterior cruciate ligament reconstruction show an asymmetrical force exertion during functional movements at the time of return to sport and for years after surgery, thus increasing the risk of reinjury.

What Is New

- Asymmetries in force exertion during eccentric and concentric actions can be early detected in the midterm after anterior cruciate ligament reconstruction by means of a countermovement jump, to promptly address rehabilitation before the return to sport. Individuals reconstructed with bone-patellar tendon-bone graft need higher attention during rehabilitation because they show greater asymmetries associated with a higher power during the countermovement jump and then individuals reconstructed with semitendinosus and gracilis graft.

Bone-patellar tendon-bone (BPTB) and semitendinosus and gracilis (STGR) tendon grafts are the two most common techniques used for surgical reconstruction of the anterior cruciate ligament (ACL). Quadriceps muscle weakness is a common issue of the two surgical techniques after ACL reconstruction; however, neuromuscular and biomechanical impairments show peculiarities for each of the two techniques. Individuals undergoing ACL reconstruction with BPTB graft show higher quadriceps strength deficits with respect to individuals reconstructed using STGR graft, as the quadriceps muscle is affected not only by ACL rupture but also by damage to the patellar tendon due to the surgical graft,[1] which persists for years after surgery.[2] Individuals with STGR graft show strength deficits of both knee extensor and flexor muscles.[3] In particular, knee flexor strength deficits after surgery persist in the long term as a consequence of a morphological degeneration of the STGR muscle-tendon units.[4]

It is thus important that exercise protocols address the specific functional deficits after ACL reconstruction within each of the two surgical techniques. However, an effective rehabilitation is strongly related to an adequate and ongoing functional assessment of physical performance.[5] Among all functional parameters that need to be monitored, including knee joint range of motion, pain, and swelling, a central role is played by muscle force exertion during functional movements.[6–8] Attention has to be given to both the operated and nonoperated

From the Department of Movement, Human and Health Sciences, University of Rome Foro Italico, Rome, Italy (L. Labanca, LC, GC, JER, PPM, AM); Institute of Human Movement Science, Sport and Health University of Graz, Graz, Austria (FB); Villa Stuart Sport Clinic-FIFA Medical Centre of Excellence, Rome, Italy (JER, PPM, AM); and Cardiff School of Sport and Health Sciences, Cardiff Metropolitan University, Cardiff, United Kingdom (L. Laudani).

All correspondence should be addressed to: Luciana Labanca, PhD, Department of Movement, Human and Health Sciences, University of Rome Foro Italico, Piazza Lauro De Bosis 6, 00135 Rome, Italy.

The data sets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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limb and also to the asymmetry in force exertion between the two limbs.[9,10]

A vertical countermovement jump (CMJ) is a task requiring muscle strength, power, and elastic response of tendons to load.[11–13] Balance and coordination between strength, power, and activation of knee extensor and flexor muscles are essential components for an optimal performance of the CMJ. In particular, the main phases of the CMJ before the take-off phase, that is, the eccentric (ECC) phase (negative velocity of the center of mass [CoM]) and the concentric (CON) phase (positive velocity of the CoM) are featured by well-defined and coordinated muscle actions of knee extensor and flexor muscles. Thus, a phase-specific analysis of vertical components of ground reaction forces recorded during these phases provides information on functional deficits affecting either knee extensor or flexor muscles, or both. It seems thus that the CMJ has the potential to monitor functional recovery in the medium and long term after ACL reconstruction. Asymmetries during the performance of a CMJ have been reported at the time of return to sport and in the long-term after ACL reconstruction.[14–18] In addition, it has been observed that these asymmetries mostly occur during the ECC phase of the jump,[16] are related to a lower subjective perceived knee function,[19] are more pronounced in BPTB than STGR individuals,[17] and lead to an overload of the contralateral limb and the other joints in the involved limb.[14,18] Therefore, assessing asymmetries in the force exertion during the medium phase of rehabilitation before return to sport is essential to plan rehabilitation programs aimed at avoiding long-term joints degeneration and occurrence of reinjury. To the best of the authors' knowledge, however, there is no information in the literature regarding the recovery of symmetry during the performance of a CMJ in the midterm after ACL surgery. The first objective of this study was hence to longitudinally assess the asymmetry in the forces exerted during the ECC and CON phases of the CMJ in male and female individuals who underwent ACL reconstruction using either BPTB or STGR tendon graft, at 3 and 6/9 mos after surgery, in comparison with a control group (CG) of healthy participants. A second aim of this study was to investigate the relation between the forces exerted during the ECC and CON phases of the CMJ and the power exerted during the performance of the CMJ. Thus, the primary hypothesis of the study is that the BPTB participants will show higher asymmetry in force exertion than STGR participants, in particular during the first assessment and in the ECC phase of the CMJ, which mostly depends on knee extensor muscles mechanics, and that an improvement in asymmetry will be observed in the second assessment compared with the first assessment, regardless of the type of graft. The secondary hypothesis of this study is that BPTB will show a lower power and a lower ECC than CON force exertion because of the higher impairment in knee extensor muscles with respect to STGR participants.

MATERIAL AND METHODS

Participants

The study was carried out on 119 individuals reconstructed using STGR graft and 146 reconstructed using BPTB graft. Inclusion criteria were: age between 18 and 50 yrs; Tegner level[20] 5–9; autologous ipsilateral BPTB or STGR graft; postsurgical functional assessment 3 mos after surgery; and between 6 and 9 mos after surgery. Exclusion criteria were: injuries or surgery to other ligaments of the knee; bone fractures; previous musculoskeletal injuries or surgery to lower limbs; sedentary lifestyle; and lack of confidence with jumping movements. Participants with associated meniscal surgery were included in the study. Participants were all operated by the same surgeon and followed the same rehabilitation. None of the patients followed any experimental training protocol during the rehabilitation. Twenty-four healthy participants were recruited as CG. Inclusion criteria were: age between 18 and 50 yrs; Tegner level 5–9; and confidence with jumping movements. Participants with a history of musculoskeletal injuries or surgery to lower limbs were not allowed to participate in the study. Detailed information on study participants is reported in Table 1. The study was approved by the institutional review board of the University of Rome Foro Italico (CARD2018-04) and was carried out in accordance with the Declaration of Helsinki. A written informed consent was obtained from all the participants. This study coforms to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement and reports the required information accordingly (Appendix 1, Supplemental Digital Content 1, http://links.lww.com/PHM/B467).

Procedures

Participants performed all functional assessments 2 times: 3 mos after surgery and between 6 and 9 mos after surgery. Anthropometric data were collected during the first visit to the laboratory. On both the assessments, after a 10-minute low intensity warm-up on a cycle ergometer, participants performed three CMJs on two force platforms. Control group participants performed the assessments two times, 3 mos one from the other.

Countermovement Jump

Participants were asked to stand in an upright position and maintain the hands on their hips during performance of the CMJ to minimize any effect of upper limbs. They were instructed to

TABLE 1. Descriptive information on study participants

	Sex	Age, yr	Body Mass, kg	Stature, cm	Tegner Level
STGR group	63 males	32.5 ± 6.8	76.9 ± 12.1	177 ± 6	6.8 ± 0.6
	56 females	27.8 ± 10.4	60.1 ± 10.3	165 ± 6	6.8 ± 1.0
BPTB group	143 males	21.6 ± 5.1	75.7 ± 8.0	179 ± 6.1	7.9 ± 1.1
	3 females	19.6 ± 5.1	61.6 ± 3.5	173 ± 7.9	9.6 ± 0.5
CG	12 males	23.9 ± 1.4	70.6 ± 6.8	177 ± 5.2	6.6 ± 1.6
	12 females	23.5 ± 1.5	59.2 ± 6.6	167 ± 5.7	7.0 ± 1.5

quickly squat with knees flexed to approximately 90 degrees and then jump immediately as high as possible without pausing (Fig. 1). Ground reaction forces were measured by means of two, six-component force platforms (KISTLER, model 9281 B; Winterthur, Switzerland; 1000-Hz sampling frequency), which were positioned below each foot. Vertical components of the ground reaction force were filtered offline using a digital, low-pass, second-order, Butterworth filter with a cutoff frequency set at 15 Hz. Signals from the two force platforms were summed and then analyzed according to previous literature.[21,22] Briefly, the vertical velocity of the CoM was calculated from the time integration of the instantaneous acceleration, as in the previous studies.[21,22] The acceleration was calculated from force signals as the ratio between the vertical force and the mass of the participant. The vertical displacement of the center of gravity (CoG) was calculated from the time integration of the velocity. The values of the minimum and maximum displacements were calculated and used to obtain the maximum vertical displacement. Power was calculated by multiplying the vertical force by the vertical velocity.[21,22] Highest power value (peak power) was calculated. The ECC and CON phases of the push-off phase of the jump were identified from vertical velocity of the jump. The ECC phase was identified from the downward movement (negative velocity) of CoM, whereas CON phase was identified from the upward movement of CoM (positive velocity), as represented in Figure 1.[21,22] Peak force recorded during both ECC and CON phases was used for further analysis. A total of three CMJ trials with 1-min rest in between were performed. The mean values of the three CMJs were calculated. Absolute peak forces of ECC phase and CON phase were normalized by body weight of each participant and used for further analysis. Side-to-side symmetry was quantified for peak forces recorded during the ECC phase and CON phase of the CMJ using the limb symmetry index (LSI).[6–8] For the participants in BPTB and STGR groups, LSI was calculated as the ratio between the operated and the nonoperated limb expressed as a percentage. For the CG, LSI was quantified as the ratio between the nondominant and the dominant limb expressed as a percentage.[6]

Data Analysis and Statistics

Descriptive statistics was used to summarize demographic and anthropometric data. Data were tested for distribution using a Shapiro-Wilk test. To address the primary hypothesis of the study, a two-way (time × group) analysis of variance (ANOVA) was performed on LSI of the ECC and CON phases of the CMJ. To address that the secondary hypothesis of the study were performed: (1) a four-way (time × group × limb × phase), ANOVA was performed, and (2) a two-way (time × group) ANOVA was performed for power exerted during the performance of the CMJ. In addition, to investigate the differences between male and female participants, a two-way

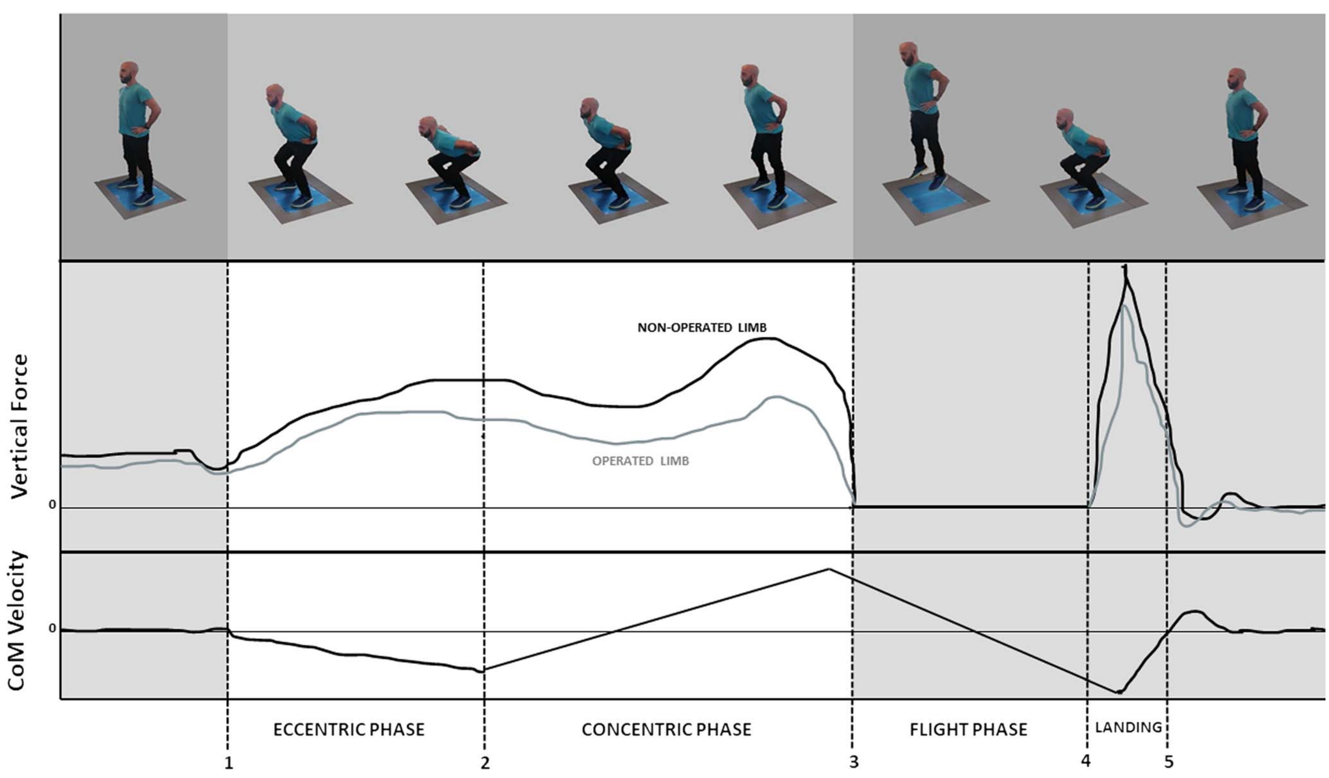

FIGURE 1. Graphical representation of the performance of a CMJ with vertical components of ground reaction forces recorded from the two force platforms, and the velocity of the CoM calculated from the time integration of the instantaneous acceleration. The CMJ has been divided into the four main phases, that is, ECC (between vertical dotted lines 1 and 2), CON (between vertical dotted lines 2 and 3), flight (between vertical dotted lines 3 and 4), and landing (between vertical dotted lines 4 and 5). In white are represented the ECC and CON phases, which were analyzed in this study. In the upper part of the figure, a sequence of photographs showing the performance of the CMJ performed over two force platforms, one below each foot. In the middle part of the figure, vertical components of ground reaction forces recorded from the two force platforms for the nonoperated (in black) and the operated (in gray) limbs. In the lower part of the figure, velocity of the CoM.

(time × group) ANOVA was performed an all the parameters. This latter was performed only for STGR group in comparison with the CG. It was not possible to perform the analysis in the BPTB group because of the low number of females. An additional two-way (time × group) ANOVA was performed to analyze data related to the CoG displacement. When the main effect F was significant, a Student t test with Bonferroni correction was used to locate significant differences. A significance level of $P < 0.05$ was adopted. Data analyses were performed with MatLab R2014a (MathWorks, Natick, MA) and SPSS 20.0 (SPSS, Inc, Chicago, IL). A post hoc power analysis was performed by means of the G*Power Software (Version 3.1.9.6).

RESULTS

Primary Hypothesis

A group × time interaction was found for LSI of peak forces recorded during the ECC phase ($F = 12.879$, $P < 0.001$) and the CON phase ($F = 29.688$, $P < 0.001$) of the CMJ. At T1 and T2, participants in the BPTB group and STGR group showed a lower LSI when compared with healthy participants. At T1, BPTB group showed a lower LSI than STGR participants. A significant increase ($P < 0.001$) of the LSI between T1 and T2 was found in both groups of ACL participants. Mean values of LSI of ECC and CON peak forces and significant differences between groups after the post hoc analysis are reported in Figure 2.

Secondary Hypothesis

In Figure 3 are illustrated means and SDs of peak forces normalized by body weight at T1 and T2 with statistical significances after the post hoc analysis. Eccentric and CON peak forces showed no significant differences across time and between the right and left limb of participants of the CG. Thus, the right limb of CG participants has been used for graphical representation of the results.

A group × time interaction ($F = 4.619$, $P < 0.05$) was found for peak power recorded during the CMJ. Both ACL groups showed a significant increase in peak power between T1 and T2 (BPTB from 3221.3 ± 707.7 to 3473.0 ± 644.4; $P < 0.001$, STGR from 2377.6 ± 695.4 to 2581.7 ± 730.5; $P < 0.001$), although no significant differences were observed in control participants between T1 and T2 (2867.3 ± 743.6 and 2975.5 ± 736.2, respectively). Participants in the BPTB group showed a significantly higher peak power when compared with STGR participants at T1 ($P < 0.001$) and T2 ($P < 0.001$). The STGR participants showed a lower peak power when compared with CG participants at T1 ($P < 0.001$) and at T2 ($P < 0.001$).

Male participants of the STGR and CGs showed significantly higher peak power values when compared with their female counterparts (Fig. 4). It was not possible to perform a statistical analysis to investigate the effect of gender on the analyzed data for BPTB participants, as that group had only three females. No significant differences were found between male participants of CG and BPTB group for peak power at T1 and T2.

The STGR group showed a significantly lower CoG displacement when compared with BPTB group and CG at T1 (51.7 ± 12.6, 61.4 ± 22.8 and 70.3 ± 12.2, respectively) and at T2 (58.9 ± 16.0, 68.1 ± 14.1 and 69.7 ± 9.9, respectively). The CoG was significantly higher at T2 respect to T1 in both BPTB group ($P < 0.001$) and STGR group ($P < 0.001$).

Statistical Power

The post hoc power analysis conducted on data related to the two main parameters of asymmetry gave a power of 95.4% for the LSI of ECC forces (effect size = 0.601, $\alpha = 0.05$) and a power of 95.9% for the LSI of CON forces (effect size = 0.521, $\alpha = 0.05$).

DISCUSSION

The main findings of this investigation, in accordance with the primary research hypothesis, were that (i) all ACL participants showed a lower interlimb symmetry in force than CG participants during both ECC and CON phases of the CMJ, (ii) BPTB showed a lower symmetry in both ECC and CON phases during the first assessment with respect to STGR participants, and (iii) an improvement, that is, a reduction of the asymmetry, between the first and the second assessment was

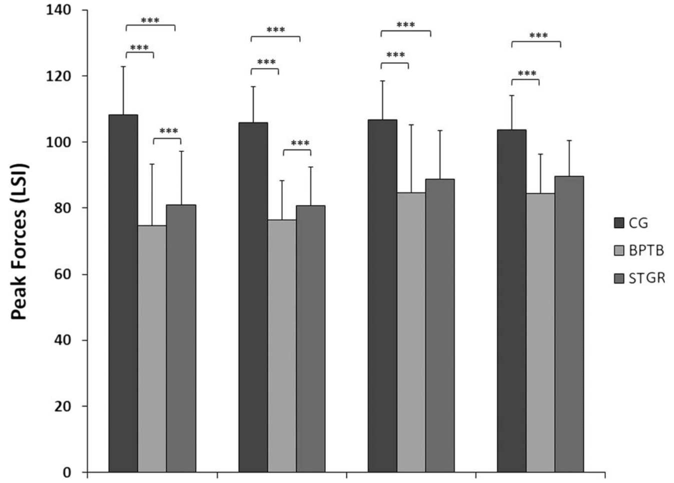

FIGURE 2. Limb symmetry index of ECC and CON peak forces in the three groups at T1 and T2. ***$P < 0.001$.

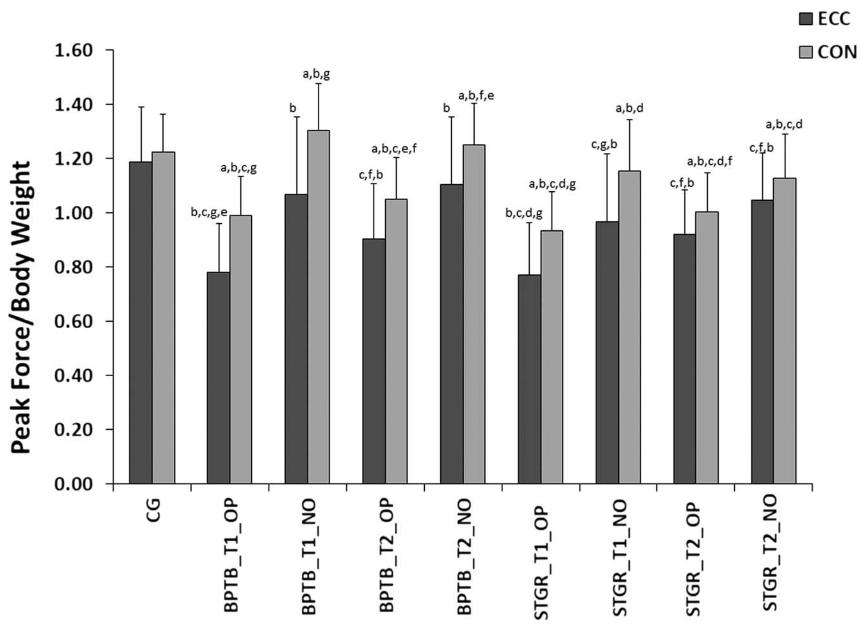

FIGURE 3. Peak forces of the ECC and CON phases of CMJ normalized by body weight in the three groups at T1 and T2. Significantly different from: [a] ECC, [b] contralateral limb, [c] CG, [d] BPTB, [e] STGR, [f] T1, and [g] T2.

observed in both groups. In addition, despite an improvement between the first and the second assessment, interlimb symmetry in force did not reach values greater than 90%, which is suggested for the return to sport activities. These results have a high relevance for the management of the postsurgical rehabilitation, because they show that ACL-reconstructed individuals need to properly address asymmetrical loading during functional tasks. Moreover, the results are in accordance with previous literature[6,7,18] reporting that this timeframe (6–9 mos after surgery) should not be considered for the return to unrestricted sport activities.

Regarding the secondary hypothesis of this study, both BPTB and STGR groups showed a lower amount of force exertion during the ECC phase of the CMJ, featured by an ECC action of the quadriceps, than during the CON phase, featured by a CON action of the quadriceps, whereas the CG showed no difference in force exertion between the two phases of the jump. The hypothesis was not confirmed because we expected to find a lower ECC than CON force exertion only in the BPTB group. In addition, the power exertion was not lower in BPTB than STGR group in both the assessments. Countermovement jump performance is well known to depend not only on the knee extensor and flexor muscles strength but also on the elastic energy exerted by tendon, which is "loaded" during the stretching of the ECC phase and then released during the CON phase of the jump. Previous research has shown that patellar tendon mechanical properties are as important as quadriceps strength and activation, for the effectiveness of the countermovement phase of the jump.[12,13,23] The ACL-reconstructed individuals have impairments both in muscle strength and tendon mechanical

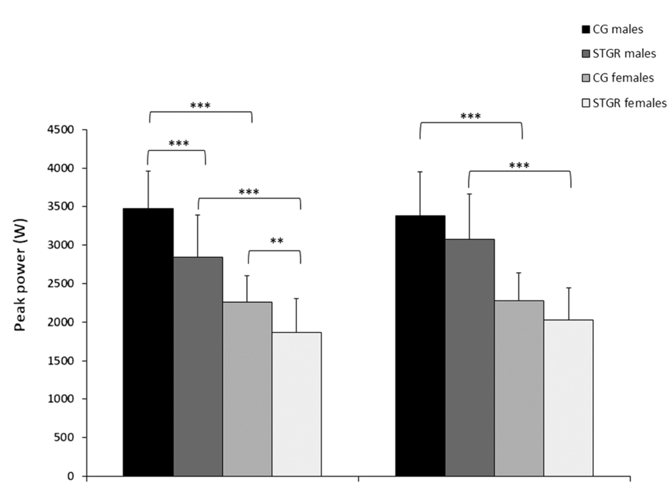

FIGURE 4. Peak power exerted during CMJ in male and female participants of CG and STGR groups at T1 and T2. $^{**}P < 0.01$, $^{***}P < 0.001$.

properties, and thus, they usually show intralimb or interlimb compensation strategies during the performance of bilateral tasks. The patients in this study showed alterations in particular during the ECC phase of the movement, showing a lower peak force with respect to the CON phase and with respect to the contralateral limb. This is in accordance with the previous investigations reporting a lower ECC impulse during CMJs.[16,19] This result was observed in particular in patients reconstructed with BPTB graft, which are known to show greater deficit in quadriceps function respect to patients with hamstrings graft, and show alterations of the mechanical properties of the patellar tendon harvested for the surgical graft.[1] Impairments have been described also in other tasks requiring ECC action of the quadriceps. Weakness of the quadriceps was reported not only during ECC isokinetic assessment[24] but also during the weight acceptance phase of walking, which requires an ECC contraction of the quadriceps, with ACL-reconstructed patients showing low ability to stabilize the lower limb.[25] It has been also reported by previous literature a correlation between poor performance during ECC actions and low perceived knee function[16,19] and a risk of reinjury in athletes showing asymmetries in the ECC phase of jumps.[15] In this study, a symmetry of 90%, which is required for the return to sport,[26] was not observed between 6 and 9 mos after surgery. This result supports the idea that in this time frame, patients are not ready for the return to sport, which should be delayed as much as possible to recover muscle strength and function and decreasing the risk of reinjury.[27]

In addition, BPTB participants showed higher peak power when compared with STGR participants and no differences with CG participants in both measurements, despite higher between-limb asymmetry. Thus, to achieve high levels of power during the CMJ performance, interlimb and intralimb compensation may have occurred. Previous literature suggests that when global performance of the jump is not affected despite an asymmetrical loading of lower limbs, there is an overloading not only of the nonoperated limb but also of the other joint of the operated limb, in particular the hip joint.[14,28] It is not surprising that contralateral injuries as well as overloading pathologies on other joint of the operated limb are extremely common after ACL surgery.[5]

The STGR participants showed higher symmetry when compared with BPTB participants but lower absolute peak forces and power. The lower performance level may be explained by two main reasons. The first is related to physical activity level of participants, which was lower when compared with BPTB participants. Thus, STGR patients might have a low level of strength and power regardless ACL injury and surgery. The second reason is represented by morphological degeneration of knee flexor muscles, which is typical in these patients.[4] Harvesting of STGR tendons for ACL graft leads to a degeneration of the two muscle bellies and a regeneration of the tendons only in few cases. Previous literature reported the important role, not only of the quadriceps muscle activation but also of knee flexor muscles activation[29,30] especially for the first phase of the countermovement and in jumping performance in general. The low muscle strength in knee flexor together with quadriceps strength deficit may have affected the overall generation of power.

The analysis of differences between sexes showed that female patients in the STGR group had lower peak power than males, but males and females had no differences in terms of asymmetry. A lower peak power was observed also in female participants of the CG when compared with their male counterpart. This should be taken into account when assessing results of a CMJ during postsurgical rehabilitation. A lower peak power in a female patient may be ascribed to a sex difference or a physical activity level difference regardless the ACL injury. Unfortunately, it was not possible to perform a between-sex differences analysis in BPTB group because of the very low number of females in this group. Future investigations should address this point.

Some limitations need to be mentioned for this study. First, the CG was not matched for physical activity level with the two groups of ACL participants. However, the first objective was to assess asymmetrical loading during a CMJ, which is due to unilateral injury or surgery, and not to other factors such as physical activity level, sex, or age. The CG was thus recruited to have normative values of symmetry in force exertion. Another limitation is represented by the low number of females in the group of BPTB participants. However, graft selection was an arbitrary decision of the surgeon and thus might not be controlled for this study. Another limitation of this study is that the second assessment of the participants was performed between 6 and 9 mos after surgery, at the time at which each patient started the return to sport phase of the rehabilitation, according to the decision of the orthopedic surgeon. We choose to assess patients according to a "functional" approach more than a "timing" approach because there is variability in the rehabilitation timing for each individual, in particular in the medium and late phases of the rehabilitation. A third limitation of this study is that only vertical components of ground reaction forces and vertical displacement of the CoG were considered. Future studies should also investigate mediolateral and anteroposterior components and displacements.

The major strength of this investigation is represented by the high number of patients involved in the study and the longitudinal follow-up across the medium phase of the rehabilitation after ACL reconstruction. It follows that this study provides useful data for clinical practice and the planning of the postsurgical rehabilitation. In addition, laboratory assessments were performed within a clinical context, thus providing highly reliable measurements and data.

CONCLUSIONS

After ACL reconstruction using either BPTB or STGR graft, patients showed asymmetries in the force exertion during a CMJ between 3 and 9 mos after surgery. Patients reconstructed using BPTB showed greater asymmetries, together with a higher peak power during the jump. Assessments of asymmetries should be performed as early as possible and specifically targeted during the rehabilitation to get patients ready for returning to sport and avoiding reinjuries. The CMJ has shown to be an effective task for the assessment of force and power exertion after ACL reconstruction, revealing differences between different groups of patients and across time. Therefore, it should be incorporated into clinical routine to improve management of patients recovering from an ACL reconstruction.

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