Title:

TIMING OF MUSCLE ACTIVATION IS ALTERED DURING SINGLE-LEG LANDING TASKS FOLLOWING ACL RECONSTRUCTION AT THE TIME OF RETURN TO SPORT

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ABSTRACT

Objectives: It is well known that alterations in landing mechanics persist for years following anterior cruciate ligament reconstruction (ACL-R)**.** Nevertheless, existing literature is controversial in reporting successful or unsuccessful recovery of pre-landing muscle activation timing after ACL-R. The study aimed at comparing myoelectric and kinematic patterns during landing tasks between ACL-R and healthy subjects.

Design: Cross-sectional study

Setting: Institutional research laboratory.

Patients and intervention: Fifteen male athletes following ACL-R using patellar tendon and 11 using hamstrings autograft at the time of return to sport were recruited. Fifteen healthy athletes served as control group. Participants performed 4 different single-leg landing tasks arriving onto a force plate.

Main outcome measures: Electromyographic (EMG) activity of knee extensors and flexors, normalized vertical ground reaction force and knee angular displacement were recorded.

Results: In all the tasks pre-impact EMG duration was longer in ACL-R (112±28 ms in the knee extensors; 200±34 ms in the knee flexors) compared to healthy participants (74±19 ms in the knee extensors; 153±29 ms in the knee flexors; $P<0.05$). Initial Contact and Maximum Post-Impact knee angle were lower in ACL-R (9±7 degrees at Initial Contact; 39±12 degrees at maximum flexion) compared to healthy participants (17±9 degrees at Initial Contact; 52±15 degrees at maximum flexion; $P<0.05$). Normalized vertical GRF was higher in ACL-R compared to healthy participants (3.4±0.5 and 2.7±0.6; $P<0.05$).

Conclusion: At the time of return to sport ACL-R subjects showed altered motor control strategies of single-leg landings. These alterations may lead to uncoordinated movement, hence increasing the risk of re-injury.

Key words: neuromuscular control, return to play, knee injury, EMG duration, motor programming, knee flexion, GRF

INTRODUCTION

Non-contact anterior cruciate ligament (ACL) injury is one of the most common knee injuries in cutting and pivoting sports such as soccer, basketball, and volleyball[1–4]. The ACL tears occur soon after the initial ground contact[5,6] and too quickly for reflexive muscular activation (>100 milliseconds) to prevent injuries [7]. Zebis et al. (2009)[8] showed that abnormal co-activation of thigh muscles performing side-cutting tasks predisposes for future ACL injury, therefore modulating muscle activity prior to landing seems to be crucial to avoid excessive joint rotations and to protect ACL from dangerous loading[9,10].

When ACL surgery is required, the reconstruction can be performed by using either autograft or allograft tissue. It has been shown that autograft is superior to irradiated allograft with regards to knee functional outcomes and laxity[11]. The standard surgical autogenous harvest sites are patellar and hamstrings tendons and it has been recently pointed out that the short and long-term outcomes of these grafts are similar in providing stability and function[12–15].

Considering the electromyographic (EMG) activity prior to landing in ACL reconstructed (ACL-R) subjects, results are controversial in reporting successful or abnormal neuromuscular strategies performing jump-landing tasks[16,17]. A recent review of Theisen et al.(2016)[10] describes in details pre-landing muscle activity in ACL injured and reconstructed subjects reviewing the literature from 1980 to 2015. The review underlined the weakness of current evidences on this topic recognizing clinical and methodological heterogeneity, such as the type of graft, time from surgery and level of physical activity as main weak points of existing studies.

The aim of this study is to compare timing and magnitude of activation of knee extensor and flexor muscles between non-professional competitive athletes who underwent ACL reconstruction with Bone-Patellar Tendon (B-PT-B) graft and Semitendinosus and Gracilis

(ST GR) tendon autograft, with respect to healthy individuals, performing single-leg landing tasks, six months after surgery (return to sport).

MATERIALS AND METHODS

Participants

This investigation was conducted as a cross-sectional study. An eligibility investigation was conducted on 108 ACL-R subjects operated by the same surgeon undergoing the 5th post-surgical time-scheduled medical examination between August and December 2015 (Figure 1).

INSERT FIGURE 1 HERE

Twenty-six ACL-R male subjects, 15 using patellar tendon (age, 21 ± 3 years (mean ± SD); stature, 1.78 ± 0.07 m; body mass, 75 ± 10 kg) and 11 using semitendinosus and gracilis autograft (age, 21 ± 5 years; stature, 1.74 ± 0.08 m; body mass, 72 ± 12 kg) were admitted in the study at 6.0 ± 1.2 months from surgery. Inclusion criteria were 1) previous history of practicing pivoting and cutting sport for at least 5 years, 2) same standardized postoperative rehabilitation protocol (table 1), 3) participation in competitive sport activities (Tegner level scale of 7-9 at the time of ACL injury) and 4) post-surgical between limb difference in anterior knee laxity < 3 mm measured by an arthrometer (Genourob, Laval, France).

INSERT TABLE 1 HERE

All ACL-R subjects were released to unrestricted sport activities by a physiatrist who attested side-to-side isometric strength of knee extensors and flexors as well as side-to-side peak vertical ground reaction force in the loading phase of a maximal vertical countermovement jump with an impairment of the surgical leg performance within 15% of the non-surgical leg . Subjects with concurrent meniscal damage treated with partial meniscectomy were included. Exclusion criteria were 1) knee pain measured by Visual Analog Scale (VAS) ≥ 4; 2) injuries of lower limb muscles during the rehabilitation process and 3) previous knee surgery. 15 healthy male subjects (age, 23 ± 2 years; stature, 1.75 ± 0.07 m; mass, 72 ± 12 kg), with no history of previous injury of muscles or joints in lower limbs and with an International Knee Documentation Committee (IKDC) score of 100, were matched with ACL-R participants according to their Tegner activity level and to their experience in pivoting/cutting sports, and served as control group. The study was approved by the Ethics Committee of the University of Rome “La Sapienza”. Informed consent was obtained from the participants and all the procedures were conducted in accordance with the Declaration of Helsinki.

Experimental setup

All the subjects performed four different single-leg landing tasks from a 20 cm height platform and at ground level arriving onto a force plate (KISTLER, model 9281 B; Winterthur, Switzerland). The examined limb was the operated knee for ACL-R group, and the dominant leg for control group. The dominant leg was defined as the leg the subject would use to kick a ball as far as possible. Wireless bipolar surface EMG electrodes were applied on the Vastus Medialis (VM), Rectus Femoris (RF), Vastus Lateralis (VL), Biceps Femoris (BF) and Semitendinosus (ST) muscles of the examined limb. Electrode position was identified between the motor point and the distal tendon, in a direction parallel to the muscle fibers in accordance with SENIAM guidelines[18]. The electrodes were applied after careful skin cleaning with ethyl alcohol. The signal was preamplified (×1,000), amplified (×1 for BF, ST and ×2 for VL,RF,VM), band-pass filtered (5 Hz–1 kHz) and high-pass filtered with a zero-lag second-order Butterworth filter with 10 Hz cutoff frequency by means of a wireless, portable EMG system (FreeEMG, BTS Bioengineering, Milan, Italy).

Angular displacement of the knee joint on the sagittal plane was recorded by an electrogoniometer (EGN) (Biometrics Ltd., Gwent, UK) placed on the lateral side of the knee with the two arms aligning with the thigh and leg axes. EGN data were low-pass filtered with a zero-lag second-order Butterworth filter with 10 Hz cutoff frequency. Previous research has shown high validity and reliability of EGN to record joint range of motion during dynamic activities[19]. EMG, force and angular data were time synchronized and collected at 1000 Hz.

Experimental Procedures

Before data collection, each subject was given 10 minutes to warm-up and practice each of the four single-leg landing tasks until comfortable. The warm-up and practice regimen was standardized to mitigate the possible variability deriving from such tasks. The takeoff platform was placed 30 cm away from the rear edge of the force plate.

The subjects were asked to stand on the takeoff platform with the reference leg, to jump forward, and land with the same leg onto the force plate. Four different landing tasks were performed. In the first, the participants were asked to land holding a bent knee position for 3 seconds (Stop Landing (STL)), In the second the participants were instructed to land as naturally as possible smoothly absorbing the impact and ending the movement in full extension (Smooth Landing (SML)), in the third the participants were asked to land and immediately perform a rebound, stopping the second landing as in the first task (rebound landing (RBL). The fourth task was the single-leg hop for distance (SLHD), in which the subjects were asked to hold the single-leg standing position on the ground with the hands placed on their iliac crests and to jump forward a distance equal to the limb length, arriving onto the force plate.

Each subject performed three trials for each task keeping the hands on their hips and wearing their own sport shoes, resulting in a total of 12 trials. The task order was randomized to reduce learning effects.

Data Management

The mean values of the 3 trials for each task were averaged, and the average was used for subsequent analysis.

The interval of interest was the initial landing phase of each jump, in particular the 200 ms around the initial contact (IC). IC was identified when the vertical ground-reaction force first exceeded 10 N.

Muscle activity onset was agreed on after visual inspection by two blinded assessor.

The following parameters were analyzed, 1) RMS EMG: magnitude of muscle activity 100 ms pre and 100 ms post IC; 2) Pre Impact EMG duration: time interval from muscle activity onset to IC; 3) vGRF/BW: peak vertical Ground-Reaction Force (vGRF) normalized by Body Weight (BW); 4) IC Knee Angle: knee flexion angle at IC instant; 5) Max Post-impact Knee Angle: peak knee flexion angle reached after IC (Fig. 2)

INSERT FIGURE 2 HERE

Normalization of EMG signal

EMG signals from knee extensors and flexors muscles were normalized by signals recorded during a maximal voluntary isometric contraction (MVIC) and expressed as a percentage. The measurement was performed with the knee at 90° of flexion in both tasks.

EMG signal during MVIC was smoothed by a symmetrical moving Root Mean Square (RMS) filter (30 ms time constant) and the peak was selected to normalize the RMS EMG data registered during the landing tasks in the given time intervals.

Statistical analysis

The statistical package IBM SPSS version 21 (IBM, Chicago, IL) was used for the analysis. All data are expressed as means ± SD. The Shapiro-Wilk test was applied before the analysis, to test the normal distribution of data.

Considering vGRF/BW, IC Knee Angle and Max Post-impact Knee Angle parameters, three separate analyses of variance (ANOVAs) with repeated measures were applied, setting the 4 tasks (i.e. Stop Landing, Smooth Landing, Rebound Landing and Hop for Distance) as within factor, and the groups (i.e. B-PT-B group, ST GR group and Control group) as between factors.

For Pre Impact EMG duration and RMS EMG in the five muscles, two separate multivariate analysis of variance (MANOVA) with repeated-measures were applied, considering the tasks as within factor, and the groups as between factors and further univariate analysis were considered only if significant multivariate effects were detected.

When a significant interaction between task and group was observed, follow-up tests were conducted by splitting the sample into three groups and running separate repeated-measures ANOVAs to explore the different effect of task on the three groups.

Post-hoc pairwise comparisons were performed by means of Fisher’s LSD test and the Bonferroni alpha level correction was applied.

The significance level for all comparisons was set at $P < 0.05$.

RESULTS

EMG data

RMS EMG data analysis showed no main effects of task, group and task by group interaction.

Pre-impact EMG duration multivariate analysis showed a main effect of task (F=14.138; P=<0.001), group (F=6.858; P=<0.001) and task by group interaction (F=2.126; P=0.001). Univariate analysis showed the same main effects for all the five muscles. Post-Hoc pairwise comparison data are shown in figure 2. Significant differences were found between ST GR and B-PT-B groups compared to Control Group for all the five muscles in all the four tasks. Specifically, the pre-impact EMG duration was found to be significantly longer in both ACL-R groups, as compared to the healthy controls. No differences were found between ST GR and B-PT-P groups. In the Hop For Distance task pre impact EMG duration was significantly longer compared to the other three tasks for all the five muscles as shown in Figure 3.

INSERT FIGURE 3 HERE

IC Knee Angle

IC Knee Angle analysis showed a main effect of group only (F=10.925; P<0.001), while no main effect for task and task by group interaction was found. Post-Hoc analysis for group showed a significant difference for control group compared to ST GR group (P=0.006) and to B-PT-B group (P<0.001). Pairwise comparison data (Table 2) showed significant differences for ST GR and B-PT-B compared to control group for 3 out of 4 tasks except for SLHD task. In particular ACL-R subjects demonstrated significantly lower IC angles. No differences were found between ST GR and B-PT-P groups.

INSERT TABLE 2 HERE

Max Post-impact Knee Angle

Max post-impact Knee Angle analysis showed a main effect of group only (F=6.702; P=0.004), while no main effect for task and task by group interaction was found. Post-Hoc analysis for group showed a significant difference for control group compared to ST GR group (P=0.009) and to B-PT-B group (P=0.017). Pairwise comparison data (Table 2) showed significantly lower peak knee flexion angles for ST GR and B-PT-B groups compared to Control group for STL and SML Tasks. No differences were found for RBL and SLHD task. No differences were found between ST GR and B-PT-P groups.

vGRF/BW

vGRF analysis showed main effects of Task (F= 6.411; p =0.004), group (F= 9.105; P=0.001) while no task by group interaction effect was found. Significant difference for smooth landing task compared to the other three tasks (Stop landing: P<0.001; Rebound landing: P=0.044; Hop for Distance: P= 0.023) was found. Post Hoc analysis for group showed a significant difference for Control group compared to ST GR group (P=0.015) and to B-PT-B group (P=0.001). Pairwise comparison data (Table 2) showed significantly higher peak vGRF/BW for ST GR and B-PT-B groups compared to Control group in STL and SML Tasks.

vGRF/BW was significantly higher in RBL for B-PT-P compared to Control group. No differences between ST GR and Control group as well as no difference between B-PT-B and ST GR was found in RBL task. No between groups differences were found in SLHD task.

DISCUSSION

The main finding of this study is that ACL-R subjects showed altered neuromuscular strategies for the control of single leg landing tasks compared to healthy controls at the time of return to sport, regardless of the type of autograft (B-PT-B or ST GR) used for the reconstruction, thus clarifying an issue which was previously controversial. In particular, they showed longer pre impact EMG duration for all the considered muscles (VM, VL, RF, BF, ST) in all the four tasks compared to control group. This result is in line with Gokeler et al. (2010)[17], who demonstrated an earlier muscle activity onset in the involved limb of ACL-R subjects both males and females compared to uninvolved limb and healthy controls performing single leg hop-for-distance task six months after surgery. Interestingly, in our study no differences were found in pre-impact EMG duration between the two ACL-R groups, suggesting that graft choice does not appear to influence the impairments in neuromuscular control of landings at the time of return to sport.

Labanca et al. (2015)[20] highlighted earlier muscle activity onset for knee extensors and flexors in ACL-R subjects compared to healthy controls after a predictable perturbation to the knee. This result is consistent with our findings, even though the time elapsed from surgery (2 vs 6 months) and the type of task were considerably different.

Our findings are in contrast with Bryant et al. (2009)[16], who showed no differences between ACL reconstructed male subjects (either using B-PT-B or ST GR autograft) and healthy controls in pre-impact EMG duration performing single leg hop for distance task 1 year after reconstruction. Since it is well established that anticipatory postural adjustments (APAs) can improve with training[21–23] and that timing of pre landing EMG activity can be modulated to the task constraints[24], it is likely that the findings of Bryant et al. (2009)[16] are biased by the fact that the authors did not take into account patients' previous experience in jumping, pivoting and cutting maneuvers[10] as well as the type of rehabilitation underwent by ACL-R subjects[25,26]. In addition, it has been shown that overall knee function returns to values similar to the contralateral limb from 8 to 12 months following ACL reconstruction[27], therefore differences between our findings and those of Bryant et al. (2009)[16] may be ascribed to the different time elapsed from surgery (6 months vs 1 year).

We found lower IC Knee Angle in 3 out of 4 tasks except for SLHD task in ACL-R subjects compared to healthy controls. It is well known that a knee angle close to full extension (0-25° of knee flexion) at toe contact in pivoting, cutting and landing movements is a risk factor for ACL injury in non-contact situations[5,6,28–31], therefore, this result is consistent with demonstrating a higher risk of re-injury in ACL-R subjects when returning to full sport participation. We did not find any significant differences in SLHD task, which could be due to the fact that SLHD was performed at ground level and not from a 20 cm height platform as in the other 3 landing tasks. It is possible to speculate that landing from a certain height maximally challenge single-leg landing ability of ACL-R limb.

Max post-impact knee angle was significantly lower between ACL-R subjects and healthy controls in STL and SML tasks. It has been previously shown that maximum knee flexion angle reached after the impact is an indicator of the efficiency of landing control capacity[9,32,33]. Reduced knee flexion at landing in ACL-R subjects may be attested to a compensatory strategy related to persistent quadriceps weakness[34], in addition, limited active flexion performing landing tasks also results in lower GRF dissipation and in a “stiff” landing pattern, which may increase ACL loading[35]. Therefore, we can assume that single-leg landing control strategies in ACL-R subjects are not efficient enough at the time of return to sport, 6 months after surgery. We did not find any significant difference in RBL and SLHD tasks even if there is a strong tendency for healthy subjects to have greater peak knee flexion angles.

In STL and SML tasks we found significantly higher vGRF/BW of ACL-R subjects compared to healthy controls. It is well established that high peak vGRF/BW in landing underlines scarce impact absorption capacity[33,36,37], and that high vGRF combined with decreased maximum knee flexion reached after IC can increase Knee Abduction Moment (KAM)[9,38,39], which is known to be one of the principal risk factors for ACL injury. In our study ACL-R groups showed both less peak knee flexion and higher peak vGRF/BW, therefore, we can state that ACL-R subjects in this condition have an increased risk of re-injury at the time of return to sport.

In RBL, vGRF/BW was significantly higher in B-PT-B compared to healthy controls. This could be ascribed to a surgery-related quadriceps weakness, which is present in B-PT-B subjects[14,40,41] when asked not only to land but also to perform a push-off from the ground, thus challenging power output, which results in a stiffer knee and in a greater vGRF/BW. No between groups differences were found for SLHD tasks probably due to the different execution of this task as previously mentioned.

The main limitation of this study is that kinematic and kinetic inter limb differences were not analyzed. Furthermore, since it is well established that neuromuscular alterations do affect the contralateral side after ACL reconstruction[42], including such analysis in the study would have helped in obtaining a deeper understanding of landing motor control adaptations following ACL reconstruction. In addition, individuals of control group were not matched for limb dominance although 19 out of 26 (73.1%) ACL-R subjects underwent injury of their dominant leg. This may have biased performance towards control group. However, since the magnitude of kinematic and kinetic asymmetry between dominant and non-dominant leg during the execution of single-leg functional tasks such as side-cutting[43] and single-leg landing[44] has previously shown to be small, we believe that the overall magnitude of bias would be negligible.

In conclusion, ACL-R subjects who returned to unrestricted sport activities 6 months after surgery showed longer pre-impact EMG duration, lower IC and Max post-impact knee angle as well as greater vGRF/BW when performing single leg landings, which is likely to increase the potential risk of re-injury. The analysis of pre-impact EMG duration performing landing tasks at the time of return to sport may be a useful tool in the decision-making process for full sport participation through the identification of subjects showing neuromuscular alterations in motor programming.

Future studies should look at which of the outcome measures that were identified as differing between ACL-R and healthy subjects are related to re-injury risk when return to sport. In addition, further investigations are needed to understand whether these neuromuscular alterations persist bilaterally over time or can be reversed by specific interventions early in the rehabilitation process..

REFERENCES

1 Arendt E, Dick R. Knee Injury Patterns Among Men and Women in Collegiate Basketball and Soccer. Am J Sports Med. 1995;23:694–701.

2 Agel J. Anterior Cruciate Ligament Injury in National Collegiate Athletic Association Basketball and Soccer: A 13-Year Review. Am J Sports Med. 2005;33:524–531.

3 Mihata LCS, Beutler AI, Boden BP. Comparing the Incidence of Anterior Cruciate Ligament Injury in Collegiate Lacrosse, Soccer, and Basketball Players: Implications for Anterior Cruciate Ligament Mechanism and Prevention. Am J Sports Med. 2006;34:899–904.

4 Prodromos CC, Han Y, Rogowski J, et al. A Meta-analysis of the Incidence of Anterior Cruciate Ligament Tears as a Function of Gender, Sport, and a Knee Injury-Reduction Regimen. Arthrosc - J Arthrosc Relat Surg. 2007;23.

5 Boden BP, Dean GS, Feagin JA, et al. Mechanisms of Anterior Cruciate Ligament Injury. Orthopedics. 2000;23:573–578.

6 Olsen OE. Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball: A Systematic Video Analysis. Am J Sports Med. 2004;32:1002–1012.

7 Hewett TE, Myer GD. The Mechanistic Connection Between the Trunk, Knee, and Anterior Cruciate Ligament Injury Timothy. Exerc Sport Sci Rev. 2014;39:161–166.

8 Zebis MK, Andersen LL, Bencke J, et al. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. Am J Sports Med. 2009;37:1967–1973.

9 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 Sport Med. 2005;33:492–501.

10 Theisen D, Rada I, Brau A, et al. Muscle activity onset prior to landing in patients

after anterior cruciate ligament injury: A systematic review and meta-analysis. PLoS One. 2016;11.

11 Kan S-L, Yuan Z-F, Ning G-Z, et al. Autograft versus allograft in anterior cruciate ligament reconstruction: A meta-analysis with trial sequential analysis. Medicine (Baltimore). 2016;95:e4936.

12 Spindler KP, Kuhn JE, Freedman KB, et al. Anterior Cruciate Ligament Reconstruction Autograft Choice: Bone-Tendon-Bone Versus Hamstring: Does It Really Matter? A Systematic Review. Am J Sports Med. 2004;32:1986–1995.

13 Sajovic M, Vengust V, Komadina R, et al. A Prospective, Randomized Comparison of Semitendinosus and Gracilis Tendon Versus Patellar Tendon Autografts for Anterior Cruciate Ligament Reconstruction: Five-Year Follow-Up. Am J Sports Med. 2006;34:1933–1940.

14 Samuelsson K, Andersson D, Karlsson J. Treatment of Anterior Cruciate Ligament Injuries With Special Reference to Graft Type and Surgical Technique: An Assessment of Randomized Controlled Trials. Arthrosc J Arthrosc Relat Surg. 2009;25:1139–1174.

15 Thompson S, Salmon L, Waller A, et al. Twenty-Year Outcomes of a Longitudinal Prospective Evaluation of Isolated Endoscopic Anterior Cruciate Ligament Reconstruction With Patellar Tendon Autografts. Am J Sports Med. 2016;43:2164–2174.

16 Bryant AL, Newton RU, Steele J. Successful feed-forward strategies following ACL injury and reconstruction. J Electromyogr Kinesiol. 2009;19:988–997.

17 Gokeler A, Hof AL, Arnold MP, et al. Abnormal landing strategies after ACL reconstruction. Scand J Med Sci Sport. 2010;20:12–19.

18 Hermens HJ, Freriks B, Disselhorst-Klug C, et al. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol.

2000;10:361–374.

19 Rowe P, Myles C, Hillmann S, et al. Validation of flexible electrogoniometry as a measure of joint kinematics. Physiotherapy. 2001;87:479–488.

20 Labanca L, Laudani L, Casabona A, et al. Early compensatory and anticipatory postural adjustments following anterior cruciate ligament reconstruction. Eur J Appl Physiol. 2015;115:1441–1451.

21 Massion J, Ioffe M, Schmitz C, et al. Acquisition of anticipatory postural adjustments in a bimanual load-lifting task: Normal and pathological aspects. Exp Brain Res. 1999;128:229–235.

22 Tsao H, Hodges PW. Immediate changes in feedforward postural adjustments following voluntary motor training. Exp Brain Res. 2007;181:537–546.

23 Kanekar N, Aruin AS. Improvement of anticipatory postural adjustments for balance control: Effect of a single training session. J Electromyogr Kinesiol. 2015;25:400–405.

24 Santello M. Review of motor control mechanisms underlying impact absorption from falls. Gait Posture. 2005;21:85–94.

25 Thomeé R, Kaplan Y, Kvist J, et al. Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. Knee Surgery, Sport Traumatol Arthrosc. 2011;19:1798–1805.

26 Yabroudi MA, Irrgang JJ. Rehabilitation and Return to Play After Anatomic Anterior Cruciate Ligament Reconstruction. Clin Sports Med. 2013;32:165–175.

27 Abrams GD, Harris JD, Gupta AK, et al. Functional Performance Testing After Anterior Cruciate Ligament Reconstruction: A Systematic Review. Orthop J Sport Med. 2014;2:2325967113518305.

28 Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of Anterior Cruciate Ligament Injury in Basketball: Video Analysis of 39 Cases. Am J Sports Med.

2006;35:359–367.

29 Oberländer KD, Brüggemann GP, Höher J, et al. Altered landing mechanics in ACL-reconstructed patients. Med Sci Sports Exerc. 2013;45:506–513.

30 Di Stasi S, Myer GD, Hewett TE. Neuromuscular Training to Target Deficits Associated With Second Anterior Cruciate Ligament Injury 2014;43:777–11.

31 Read PJ, Oliver JL, De Ste Croix MBA, et al. Neuromuscular Risk Factors for Knee and Ankle Ligament Injuries in Male Youth Soccer Players. Sport Med. 2016;46:1059–1066.

32 Benjaminse A, Otten B, Gokeler A, et al. Motor learning strategies in basketball players and its implications for ACL injury prevention: a randomized controlled trial. Knee Surgery, Sport Traumatol Arthrosc. 2017;25:2365–2376.

33 Schmitt LC, Paterno M V., Ford KR, et al. Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. Med Sci Sports Exerc. 2015;47:1426–1434.

34 Xergia S a, 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;43:154–162.

35 Laughlin WA, Weinhandl JT, Kernozek TW, et al. The effects of single-leg landing technique on ACL loading. J Biomech. 2011;44:1845–1851.

36 Mizrahi J, Susak Z. Analysis of parameters affecting impact force attenuation during landing in human vertical free fall. Eng Med. 1982;11:141–147.

37 Dufek JS, Bates BT. The evaluation and prediction of impact forces during landings. Med Sci Sports Exerc. 1990:370–377.

38 Podraza JT, White SC. Effect of knee flexion angle on ground reaction forces, knee moments and muscle co-contraction during an impact-like deceleration landing: Implications for the non-contact mechanism of ACL injury. Knee. 2010;17:291–295.

39 Aerts I, Cumps E, Verhagen E, et al. A systematic review of different jump-landing variables in relation to injuries 2013;53:509–519.

40 Laudani L, Giombini A, Mariani PP, et al. Application of the sit-to-stand movement for the early assessment of functional deficits in patients who underwent anterior cruciate ligament reconstruction. Am J Phys Med Rehabil. 2014;93:189–199.

41 Labanca L, Laudani L, Menotti F, et al. Asymmetrical Lower Extremity Loading Early After Anterior Cruciate Ligament Reconstruction Is a Significant Predictor of Asymmetrical Loading at the Time of Return to Sport. Am J Phys Med Rehabil. 2015;95:1.

42 Benjaminse A, Holden S, Myer GD. ACL rupture is a single leg injury but a double leg problem: too much focus on ‘symmetry’ alone and that’s not enough! Br J Sports Med. 2018;0:bjsports-2017-098502.

43 Greska EK, Cortes N, Ringleb SI, et al. Biomechanical differences related to leg dominance were not found during a cutting task. Scand J Med Sci Sport. 2017;27:1328–1336.

44 van der Harst JJ, Gokeler A, Hof AL. Leg kinematics and kinetics in landing from a single-leg hop for distance. A comparison between dominant and non-dominant leg. Clin Biomech. 2007;22:674–680.

FIGURE LEGEND

Figure1

Flowchart showing patients recruitment.

Figure2

An example of raw rectified EMG activity of VM, vertical GRF and sagittal Angular displacement in a STL task. The dotted line represent the EMG activity onset and the full line represent the initial ground contact.

Figure3

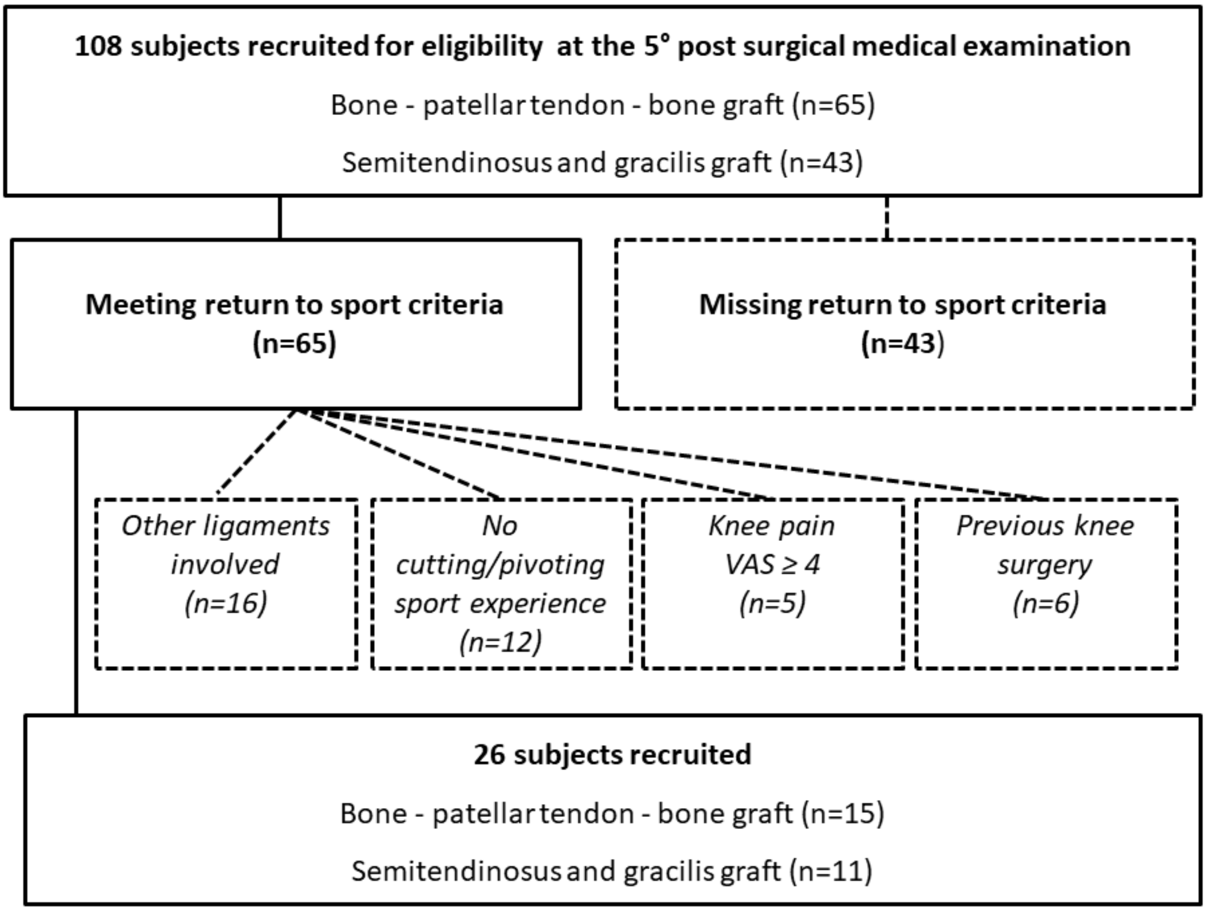
Pre-Impact EMG duration in all the 4 tasks. the black column represents B-PT-P group, the grey line represents ST GR group and the white column represents CONTROL group. *=P<0.05; **=P<0.01; ***=P<0.001.

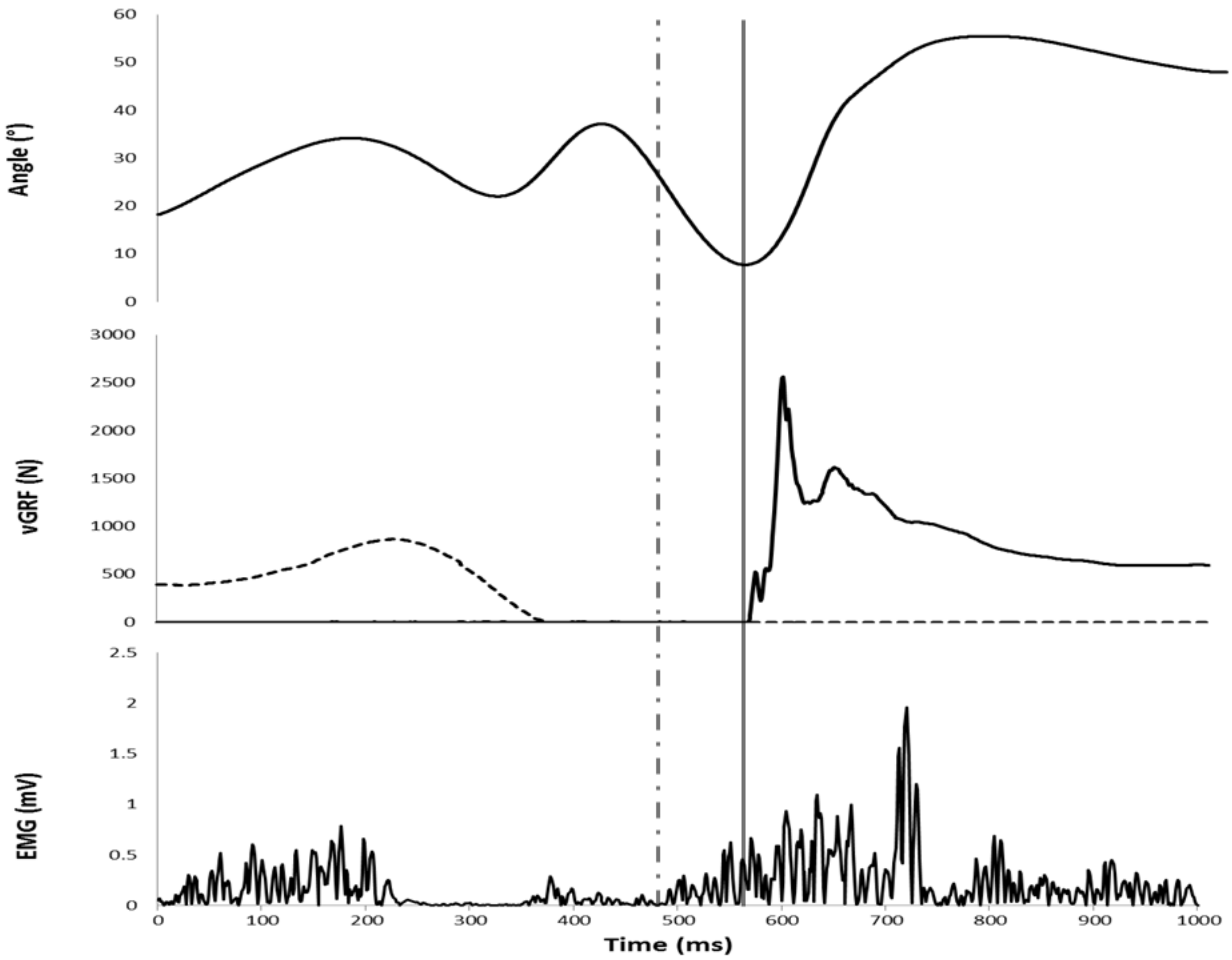
TABLE 1	
Post-Surgery ACL Rehabilitation (2nd day to 6th month)	
1st and 2nd week	
	Weight bearing with brace
	Passive mobilization
	Quadriceps NMES
	Straight leg raises
	Hamstrings stretching
2nd to 4th week	
	Weight bearing with brace
	Active mobilization
	Squatting exercises
	Passive quadriceps NMES
	Straight leg raises
	Hamstrings stretching
4th to 8th week	
	Full ROM recovery
	Weight bearing without brace
	Active mobilization
	Squatting exercises
	Quadriceps NMES
	CKC resistance training
	Quadriceps stretching
	Hamstrings stretching
8th to 12th week	
	Running pattern recovery
	Heavy CKC resistance training
	OKC resistance training
	Squatting exercises
	Quadriceps stretching
	Hamstrings stretching
12th week to 6th month	
Autonomous gym training 3 x week	

TABLE 2

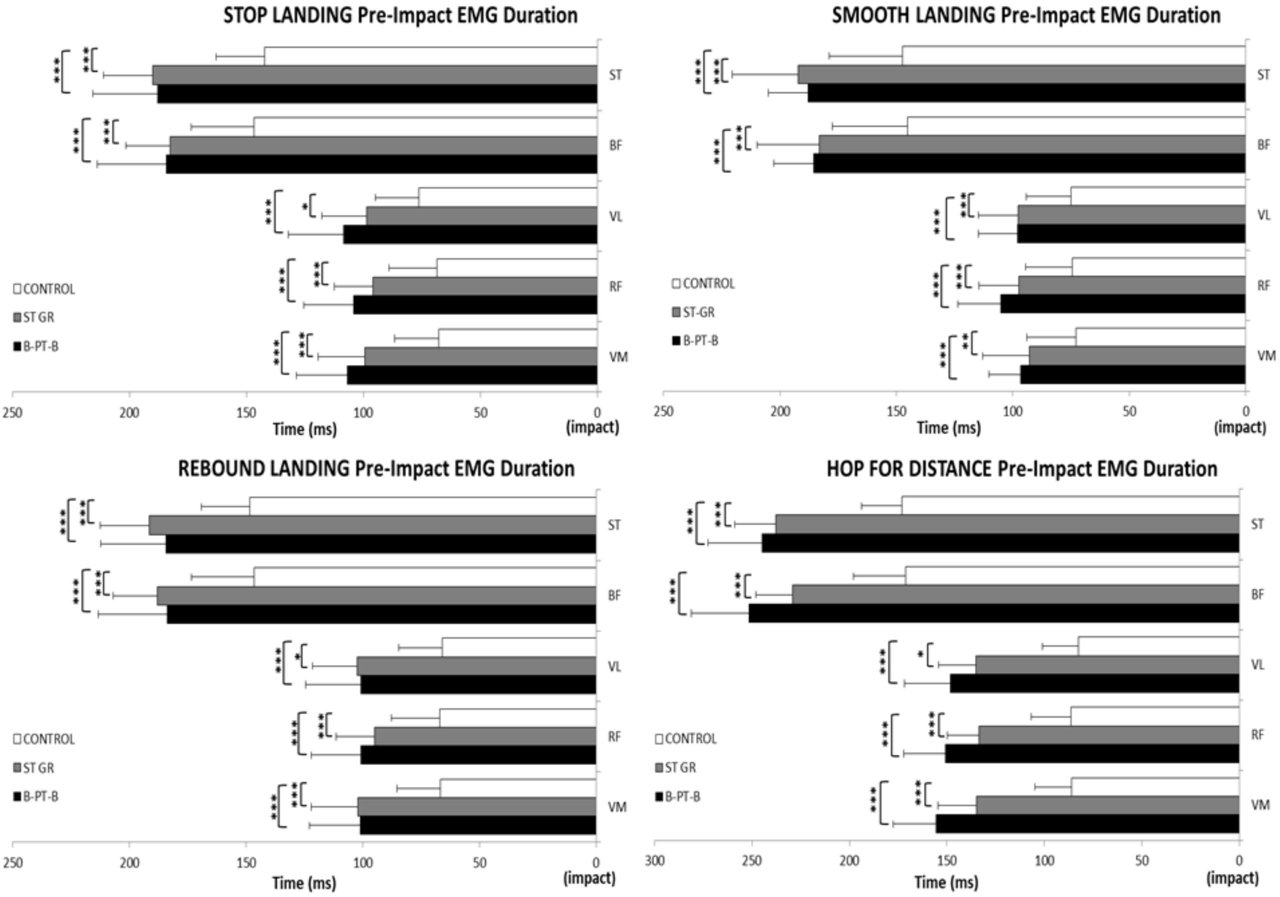
	STOP LANDING			SMOOTH LANDING			REBOUND LANDING			HOP FOR DISTANCE		
	B-PT-B	ST-GR	CONTROL	B-PT-B	ST-GR	CONTROL	B-PT-B	ST-GR	CONTROL	B-PT-B	ST-GR	CONTROL
vGRF/BW	3.4 ± 0.8	3.5 ± 0.4	2.8 ± 0.6[c]	3.0 ± 0.6	3.1 ± 0.5	2.5 ± 0.5[b]	3.5 ± 0.4[d]	3.1 ± 0.5	2.8 ± 0.6	3.5 ± 0.9	3.6 ± 0.7	2.8 ± 0.5
IC Knee Angle (°)	7.2 ± 4.5	10.4 ± 5.9	20.1 ± 11.1[a]	7.7 ± 5.2	10.2 ± 7.0	18.1 ± 7.2[a]	9.0 ± 8.1	10.0 ± 8.1	18.3 ± 8.4[a]	10.1 ± 6.9	10.04 ± 7.3	13.9 ± 8.2
Max post-impact knee angle (°)	38.8 ± 11.2	36.1 ± 11.5	55.2 ± 14.1[b]	42.2 ± 12.1	35.3 ± 12.5	57.9 ± 14.4[b]	40.0 ± 14.4	39.5± 10.7	52.0 ± 13.3	39.2 ± 13.1	37.8 ± 10.5	44.4 ± 13.0

Table 2 vGRF/BW, IC knee angle and Max post-impact knee angle data for the 3 groups in the 4 tasks. a = significantly different from B-PT-B and ST-GR, P=<0.05; b= significantly different from B-PT-B and ST-GR, P=<0.01; c= significantly different from B-PT-B and ST-GR, P=<0.001; d= significantly different from CONTROL, P=<0.05


108 subjects recruited for eligibility at the 5° post surgical medical examination
Bone - patellar tendon - bone graft (n=65)
Semitendinosus and gracilis graft (n=43)
Meeting return to sport criteria (n=65)
Missing return to sport criteria (n=43)
Other ligaments involved (n=16)
No cutting/pivoting sport experience (n=12)
Knee pain VAS ≥ 4 (n=5)
Previous knee surgery (n=6)
26 subjects recruited
Bone - patellar tendon - bone graft (n=15)
Semitendinosus and gracilis graft (n=11)



Angle (°)
60
50
40
30
20
10
0
vGRF (N)
3000
2500
2000
1500
1000
500
0
EMG (mV)
2.5
2
1.5
1
0.5
0
0
100
200
300
400
500
600
700
800
900
1000
Time (ms)


STOP LANDING Pre-Impact EMG Duration
SMOOTH LANDING Pre-Impact EMG Duration
REBOUND LANDING Pre-Impact EMG Duration
HOP FOR DISTANCE Pre-Impact EMG Duration
ST
BF
VL
RF
VM
□ CONTROL
▨ ST GR
■ B-PT-B
Time (ms)
(impact)
300
250
200
150
100
50
0
*
***