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Postural adjustments following ACL rupture and reconstruction: a longitudinal study

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TITLE

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ABSTRACT

Compensatory and anticipatory postural adjustments of muscles acting on the knee are altered early after anterior cruciate ligament reconstruction (ACLr). This study aimed to investigate longitudinal changes in compensatory and anticipatory postural adjustments from ACL rupture until return to play after ACLr. Twelve ACL-injured participants (ACL-P) were asked to respond to unpredictable and predictable perturbations administered to the injured knee before (T1), 2 (T2) and 6 months after (T3) ACLr. Twelve healthy participants served as controls. Compensatory and anticipatory latencies of vastus lateralis (VL) and medialis (VM) were measured with respect to the arrival of perturbations. ACL-P showed delayed compensatory latencies compared to controls at T1 for VL (101 ± 32 ms vs 63 ± 7 ms; $p < 0.01$) and VM (117 ± 36 ms vs 75 ± 17 ms; $p < 0.01$) and at T2 for VL (94 ± 20 ms vs 63 ± 7 ms; $p < 0.001$) and VM (94 ± 27 ms vs 71 ± 11 ms; $p < 0.05$). ACL-P showed earlier anticipatory latencies than controls for VL at T1 (-69 ± 44 ms vs -12 ± 12 ms; $p < 0.05$) and T2 (-46 ± 17 ms vs -16 ± 12 ms; $p < 0.05$). At T3, ACL-P showed delayed compensatory latencies for VL (91 ± 18 ms vs 56 ± 21 ms; $p < 0.001$) and VM (95 ± 13 ms vs 66 ± 4 ms; $p < 0.001$), whilst anticipatory latencies were restored. Rehabilitation should address delayed compensatory responses.

INTRODUCTION

Rupture of the anterior cruciate ligament (ACL) is one of the most common knee injuries in people who practice cutting and pivoting sport activities [12]. Short- and long-term deficits in neuromuscular function have been reported following ACL reconstruction, which may increase the risk of re-injury and jeopardize the return to play [15,16]. Therefore, early identification of neuromuscular deficits has been advocated to prevent long-term loss of muscle function and to maximise functional recovery following ACL injury and surgery [16,20,21,22].

Stabilization of the knee joint is known to play a major role in preventing injuries of the lower limb during daily life and sport activities [16]. Non-contact injuries of the ACL have been reported to occur as a consequence of sudden disturbances/perturbations to the knee position during the ongoing voluntary movement of the lower limb [15]. From a neuromechanical point of view, joint stabilization is achieved during voluntary movement by compensatory and anticipatory postural adjustments aimed at minimizing unpredictable and predictable perturbations, respectively [4,18,20]. A number of studies have therefore assessed the ability to respond to sudden knee perturbations during the performance of whole-body voluntary movements [10,11,25,28]. Results of these studies showed that abnormal responses to predictable/unpredictable perturbations can be observed for years after ACL surgery; in turn, this might lead to functional instability during daily living tasks [5,10,28] and, hence, increased risk of re-injury [29]. However, weight bearing during challenging postural conditions is not safe early after ACL injury or surgery. Labanca et al. [20] dealt with this issue by designing a novel perturbation task to evaluate both compensatory and anticipatory responses to unpredictable and predictable postural perturbations, respectively, of the knee joint during the early phase after ACL reconstruction. The perturbation task involved unloaded perturbations applied to the knee

joint in a sitting position, thus being safe also in the early phase after surgery. Abnormalities in both compensatory and anticipatory strategies in the knee extensor muscles were present at two months from surgery. It is not known, however, whether these abnormalities may change over time and can improve by the time of return to sport.

Monitoring of abnormalities in postural adjustments before surgery and along the course of the rehabilitation within a clinical context could provide novel and meaningful insights to facilitate to the design of effective ad-hoc rehabilitation protocols, thus avoiding long-term functional deficits in ACL operated individuals. Therefore, the aim of this study was to investigate compensatory and anticipatory responses of the knee extensor muscles to unpredictable and predictable perturbations, respectively, with a longitudinal design from the time of ACL rupture up to 6 months following ACL reconstruction.

METHODS

The study was conducted on male participants who underwent ACL reconstruction (ACL participants) and healthy male participants. Physical activity level before injury was evaluated in all participants by means of the Tegner Activity Level Scale [35] and those with an activity level between 5 and 7 were included in the study. Both groups were matched for physical activity levels. All participants were assessed three times: ACL participants were tested before ACL surgical reconstruction (T1), two months after surgery (T2), and six months after surgery (T3); three experimental testing sessions were carried out also for healthy participants to understand the possible effects of task familiarisation. These occurred over the same timescale as the ACL participants, i.e. the first as a baseline and the second and third, two and six months after the first, respectively. The study was carried out in accordance with the Declaration of Helsinki and the IJSM's ethical standards [13], with ethics committee approval from the University of Rome "La Sapienza". Informed consent was obtained from all the participants.

An eligibility investigation was initially conducted on twenty-five ACL participants, who were scheduled for a bone-patellar tendon-bone (BPTB) autograft surgical reconstruction of the ACL. Preoperative inclusion criteria were knee joint range of motion of at least 0 to 100 degrees of knee flexion and lack of pain and swelling of the knee joint. Exclusion criteria were concomitant injury to any other knee ligament or lower limb muscle, associated meniscus tear, and previous surgery on either knee. Postoperative inclusion criteria at T2 and T3 were adherence to the prescribed rehabilitation program, full recovery of the knee joint range of motion and the absence of pain, locking and swelling of the knee joint. Twenty ACL participants were eligible and completed the first pre-operative assessment. The remaining five ACL participants were excluded as they had concomitant injury to other ligaments of the knee (3/5) or

locking of the knee joint (2/5). The second assessment, two months after surgery, was completed by fifteen patients. Two ACL participants were excluded as they were unable to correctly perform the perturbation task (e.g., not able to completely relax quadriceps muscle during the task execution). Three ACL participants were excluded because they did not adhere to the prescribed rehabilitation. At the third assessment, six months after surgery, three ACL participants decided to drop-out of the study, thus twelve ACL participants completed all the measurements.

The twelve ACL participants (age: 21 ± 3 years; body mass: 79 ± 16 kg; height: 1.82 ± 0.04 m) had an unilateral isolated rupture of the ACL in the dominant limb. The dominant limb was determined by asking the participants which leg they use to kick a ball [7,24]. Arthroscopic ACL reconstruction was performed by only one surgeon from 10 to 30 days after ACL injury at the "Villa Stuart" Sport Clinic in Rome. After ACL reconstruction all participants were asked to undertake a standardized rehabilitation protocol under supervision of a physical therapist 5 days per week, as described by Laudani et al [22]. Briefly, the early phase of rehabilitation (0-2 months) involved continuous passive mobilizations, followed by neuromuscular electrical stimulations, isometric straight leg rises, squatting exercises, strengthening exercises and hydrokinesis. From the third to the sixth month, the rehabilitation programme consisted of muscle strength and power training, followed by sport skill acquisition exercises. All ACL participants of the present study were cleared to return to sport activities six months after surgery by the medical team.

Twelve male healthy participants (age: 23 ± 2 years; body mass: 68 ± 5 kg; height: 1.76 ± 0.05 m) were recruited. Inclusion criteria were absence of disorder or history of knee injury.

Participants were not allowed to participate in the second and third experimental session if they sustained lower limb injuries in the six month duration of the study.

Data collection took place in an isolated room and participants were blindfolded to eliminate visual input during testing. For the perturbation task participants wore loose-fitting shorts and sat comfortably above a raised plinth in a semi-reclined position and inclined approximately 40° from the horizontal. The perturbation task had two conditions, unpredictable and predictable, as described by Labanca et al [20]. Briefly, prior to each perturbation trial, the examined limb, i.e., the injured knee of ACL participants and the dominant knee of healthy participants, was placed in a reference position with the knee joint in full extension (e.g., thigh and shank aligned while maintaining the thigh in contact with the seat). Participants were instructed to fully relax the muscles of the examined limb before the perturbation. The limb was then dropped either by the experimenter, i.e., unexpected perturbation (unpredictable condition) or by the participant's contralateral limb, i.e., expected perturbation (predictable condition). During the unpredictable condition, the experimenter entirely supported the participant's involved limb with his palm open under the heel and, after 8–12 s, unexpectedly removed his palm. Participants were instructed to resist the perturbation and restore the full extension reference position as quickly as possible. During the predictable condition, participants placed their contralateral big toe under the heel of the involved limb, which was then entirely supported and kept in the reference position. After a verbal signal by the experimenter, participants were instructed to wait 8-12 s (consistent with the unpredictable task) and then quickly move away the supporting limb, while maintaining the involved limb in full extension. Each participant completed one series of 5 consecutive predictable perturbation trials and one series of 5 consecutive unpredictable perturbation trials, in a random order. We compared the injured/operated limb of ACL participants to the dominant

limb of healthy participants rather than to the contralateral limb of ACL participants, in order to rule out any intra-individual learning effect and to account for neural adaptations to ACL injury affecting both limbs [2]. All experimental sessions were conducted by the same experimenter to prevent inter-operator variability. Responses to perturbations were real-time monitored to detect irregularities in the performance, such as the inability to completely relax the quadriceps before the perturbation or to respond to the perturbations as requested. If irregularities occurred for two or fewer trials, new trials were performed. Participants who performed incorrect trials more than two times were excluded from the analysis to minimise the learning effect [1]. Successive trials were separated by a minimum of 60 s. The participants were allowed to rest 5 min between series.

At each experimental session angular displacement of the knee joint was recorded by means of an electrogoniometer (Biometrics Ltd., Gwent, UK) placed on the lateral side of the involved limb with the two arms aligning with the thigh and leg axes. Electromyography (EMG) data were collected using a portable wireless device (FreeEMG, BTS, Milan, Italy). Surface electrodes were placed over the vastus lateralis (VL) and vastus medialis (VM) muscles of the involved limb, and the VL of the uninvolved limb (UVL). For each muscle, after appropriate skin cleaning, two electrodes were attached 0.02 m apart (centre-to-centre) on the skin half way between the centre of the belly and the distal myotendinous junction, in accordance with SENIAM recommendations [14]. As EMG traces are strongly influenced by the distance between the electrodes and the innervation zones of the muscles [26], reproducibility of electrode positioning was ensured by marking the initial electrode position together with subjects' skin characteristics on a transparent tracing sheet [23], which was then used to re-mark the same position for the second and third testing sessions. Electrogoniometer and EMG signals were

sampled at 1 kHz by a portable device (FreeEMG, BTS, Milan, Italy). Kinematic data were low-pass filtered with a zero-lag second-order Butterworth filter with 10 Hz cutoff frequency. EMG signals were first high-pass filtered at 20 Hz to remove movement artifacts, and then full-wave rectified for further signal conditioning. No additional filters were applied to avoid excessive smoothing of the very early response/increase in muscle activity, which could mislead identification of the actual onset latency. In the unpredictable condition, the time of perturbation onset was identified by the onset of knee angular displacement, which was agreed on by two of the experimenters after visual inspection of the kinematic trace. The latency of compensatory muscle responses of the involved limb was evaluated with respect to the onset of knee angular displacement. In the predictable condition, the time of perturbation onset was identified as the offset of the UVL by visually inspecting the EMG trace of the muscle, and defined as the moment when the background EMG activity dropped to a minimum, as in Labanca et al [20]. The latency of anticipatory muscle responses of the involved limb was evaluated with respect to the onset of postural perturbation. Onset of either compensatory or anticipatory muscle responses was agreed by two of the experiments after visual inspection of the processed EMG signal (Figure 1a and 1b, respectively).

Insert Figure 1 here.

Descriptive statistics were used to summarize demographic data. A two-factor repeated-measures analysis of variance (ANOVA) was performed to evaluate the effects of group (ACL and healthy) and time (T1, T2 and T3) as independent variables on the onset latency of VL and VM muscles as dependent variables. The ANOVA was performed for each of the two conditions

(unpredictable and predictable). When the main effect F value was significant, pairwise comparisons with Bonferroni correction were performed and a Student's t-test was used to locate the significant differences. All analyses were performed using SPSS version 20.0 (SPSS, Inc, Chicago, IL). A significance level of $p < 0.05$ was adopted.

RESULTS

In the unpredictable condition there was a main effect of group on muscle response latencies of VL (F = 23.813; P < 0.01) and VM (F = 13.852; P < 0.01). The post-hoc analysis showed that ACL participants had higher latency of compensatory responses than healthy participants for VL (Figure 2a) and VM (Figure 2b) at T1 (a delay of 39 ms for VL and 42 ms for VM), T2 (a delay of 31 ms for VL and 23 ms for VM) and T3 (a delay of 34 ms for VL and 28 ms for VM).

Insert Figure 2 here.

In the predictable condition there was a significant group by time interaction for VL (F = 6.414; P < 0.05). ACL participants showed significantly earlier responses in VL when compared with healthy participants at T1 (-69 ± 45 ms vs -12 ± 12 ms; P < 0.05) and T2 (-47 ± 17 ms vs -16 ± 13 ms; P < 0.01). At T3 no differences were observed between the two groups. In ACL participants a significant difference was found between T1 and T3 (-69 ± 45 ms vs -9 ± 20 ms; P < 0.01), and between T2 and T3 (-47 ± 17 ms vs -9 ± 20 ms; P < 0.01) (Figure 3). No differences between the two groups were found for VM.

Insert Figure 3 here.

DISCUSSION

The main result of this study was that ACL injured participants showed delayed compensatory responses to unpredictable perturbations around the knee joint compared to healthy participants, and did not improve 2 and 6 months after ACL reconstruction. In particular, at the time of return to sport (i.e. 6 months after surgery), ACL participants showed a mean delay of 34 ms for VL and 28 ms for VM compared to healthy participants. In contrast, there was no difference in anticipatory responses to predictable perturbations between ACL and healthy participants after 6 months from surgery, thus indicating a complete recovery of anticipatory mechanisms by the time of return to sport.

Two mechanisms may explain the delayed responses to unpredictable perturbations, the first being an impaired detection of sudden change in the quadriceps muscle length as a result of the leg fall, and the second being a failure in generating a fast muscle activation in response to the perturbation. It has been shown that afferences arising from the ACL have a direct effect on gamma motoneurones acting on muscles spindles of the quadriceps femoris muscle [19,,33]. The injury related loss of these afferences, therefore, could attenuate the gamma activity, thus altering the sensitivity of muscle spindles to sudden muscle length changes. In addition, ACL rupture and its surgical reconstruction cause damages to other receptors located in the knee joint and in the skin surrounding the joint [31,33], which could contribute to the delay in detecting the quadriceps muscle lengthening and the fall of the leg by the central nervous system [3,19,20,30,31]. This is in agreement with previous studies showing impaired joint position sense following ACL rupture and reconstruction [6,32,34]. Nonetheless, the delayed generation of a fast muscle response to the perturbation could also be a result of arthrogenic muscle inhibition (AMI), which is referred to as an ongoing neural inhibition, mostly affecting high threshold

motor units, that prevents the central nervous system from fully activating the quadriceps [17,19].

It should also be mentioned that participants of this study underwent ACL reconstruction using patellar tendon graft. The perturbation task proposed in this study was aimed at generating perturbations for the knee extensor mechanisms. Thus, it is reasonable that this type of graft would affect responses to perturbations more than other type of grafts [8,9,36]. In response to predictable perturbations, the central nervous system must predict and prevent the consequences of the forthcoming perturbation by pre-planning and launching anticipatory responses earlier than the beginning of the expected perturbation itself, hence bypassing long delays associated with reflex feedback responses [4]. Therefore, the earlier timing of anticipatory responses in ACL participants before and early after surgery than in healthy participants may be related to an altered knowledge of the limb properties by the central nervous system, as a result of the disrupted ACL-related sensorial information from the knee joint. By the time of return to sport, however, such abnormalities in anticipatory timing moved back to normal, as there were no differences in the latency of anticipatory responses between ACL reconstructed and healthy participants. This might be attributed to a learning-related adaptation by the central nervous system in pre-planning anticipatory response to reduce the effects of forthcoming perturbations, despite the impaired sensory information from the ACL.

It is now recognised that the return-to-sport phase of recovery after knee surgery must be progressed by functional goals, which should be objectively quantified to choose whether to move from one phase of rehabilitation to the next [22,27]. Furthermore, it has been shown that functional deficits in the earliest postoperative phases are significant predictors of functional recovery at the time of return to sport [21], thus highlighting the importance of early

identification and quantification of lower limb deficits. The present study showed that abnormalities in compensatory postural mechanisms can be effectively identified and quantified by means of our joint perturbation task since the time of ACL rupture, as early as 2 months from surgery, and up to the time of return to play. In addition, the joint perturbation task was effective in evaluating a gradual adaptation/recovery of anticipatory postural mechanisms within six months from surgery.

A limitation of the study is that perturbations were manually delivered by an operator. An automatized system would have been able to deliver identical perturbations over time, even if less accessible for common use. Another limitation of the study is that results cannot be generalized to the whole population as only subjects with a 5 to 7 Tegner level were included in the study, thus excluding sedentary individuals and top-level athletes. Future studies should investigate postural adjustments in these patients, and clarify if physical activity levels have an effect on postural control mechanisms.

CONCLUSION

The results of this study showed that at the time of the return to sport following ACL reconstruction, compensatory postural responses of the lower limb muscles to unpredictable perturbations of the knee joint were altered/delayed in ACL participants compared to healthy participants, while anticipatory responses to predictable perturbations were not different between ACL reconstructed and healthy participants. Therefore, it may be suggested that the earliest goals after ACL reconstruction should be to target compensatory adjustments, e.g., by stimulating the ability to quickly detect sudden changes in muscle length in response to unexpected perturbations, in order to improve/recover functional stabilization of the knee joint

by the time of return to sport. Future studies should also investigate the relationship between the delay of compensatory postural responses and the neuromechanical deficits observed during demanding functional and sport-specific movements, such as walking, running, cutting or landing tasks.

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FIGURES LEGENDS

Figure 1. Representative traces recorded in one trial of the unpredictable condition (a) and one trial of the predictable condition (b). Knee joint angular displacement is represented on the upper trace. Full-wave rectified and filtered EMG traces of the VL (a and b) and UVL (b) are represented in the traces below the knee joint angular displacement trace. The perturbation is represented by the vertical continuous line. The onset of compensatory and anticipatory muscle activation is represented by the vertical dotted line.

Figure 2. Latency of compensatory VL (a) and VM (b) muscle response in the ACL group and in healthy participants at T1 (before ACL reconstruction), T2 (two months following ACL reconstruction and at T3 (six months following ACL reconstruction). Data are presented as mean and standard deviation. Significant differences between groups: * $P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

Figure 3. Latency of anticipatory VL muscle response in the ACL group and in healthy participants at T1 (before ACL reconstruction), T2 (two months following ACL reconstruction) and at T3 (six months following ACL reconstruction). Data are presented as mean and standard deviation. Significant differences between groups: * $P < 0.05$, **$P < 0.01$, ***$P < 0.001$. Significant differences between time points in ACL group: [a] different from T1, [b] different from T2, [c] different from T3.