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Stavros Ristanis, MD, Elias Tsepis, PhD, Dimitrios Giotis, MD, Nicholas Stergiou, PhD, Guiliano Cerulli, MD, Anastasios D. Georgoulis, MD

Abstract

Background

Changes in electromechanical delay during muscle activation are expected when there are substantial alterations in the structural properties of the musculotendinous tissue. In anterior cruciate ligament reconstruction, specific tendons are being harvested for grafts. Thus, there is an associated scar tissue development at the tendon that may affect the corresponding electromechanical delay.

Purpose

This study was conducted to investigate whether harvesting of semitendinosus and gracilis tendons for anterior cruciate ligament reconstruction will affect the electromechanical delay of the knee flexors.

Study Design

Case-control study; Level of evidence, 3.

Methods

The authors evaluated 12 patients with anterior cruciate ligament reconstruction with a semitendinosus and gracilis autograft, 2 years after the reconstruction, and 12 healthy controls. Each participant performed 4 maximally explosive isometric contractions with a 1-minute break between contractions. The surface electromyographic activity of the biceps femoris and the semitendinosus was recorded from both legs during the contractions.

Results

The statistical comparisons revealed significant increases of the electromechanical delay of the anterior cruciate ligament–reconstructed knee for both investigated muscles. Specifically, the electromechanical delay values were increased for both the biceps femoris (P = .029) and the semitendinosus (P = .005) of the reconstructed knee when compared with the intact knee. Comparing the anterior cruciate ligament–reconstructed knee against healthy controls revealed similar significant differences for both muscles (semitendinosus, P = .011; biceps femoris, P = .024).

Conclusion

The results showed that harvesting the semitendinosus and gracilis tendons for anterior cruciate ligament reconstruction significantly increased the electromechanical delay of the knee flexors. Increased hamstring electromechanical delay might impair knee safety and performance by modifying the transfer time of muscle tension to the tibia and therefore affecting muscle response during sudden movements in athletic activities. However, further investigation is required to identify whether the increased electromechanical delay of the hamstrings can actually influence optimal sports performance and increase the risk for knee injury in athletes with anterior cruciate ligament reconstructions.

Keywords
anterior cruciate ligament reconstruction, electromechanical delay, hamstrings, isometric contractions

The selection of the graft type that should be used for anterior cruciate ligament (ACL) reconstruction remains an issue of great concern to orthopaedic surgeons and is a very important research topic in orthopaedics.[16,27] This research is focused on how the selection of the graft relates to functional recovery after ACL reconstruction and is frequently conducted using analysis of movement with electromyographic (EMG) data.[2] Electromyographic data are specifically used as an indication of the activation patterns of separate muscles and, along with the profiles of net joint moments and powers, can be used to define the relationship between EMG activity and the mechanical response of a muscle after ACL reconstruction.[28] Some researchers have suggested that measurement of the time delay between the onset of muscle stimulation by the alpha motoneuron to the development of torque at a given joint can reveal the true effectiveness of the muscles to provide mechanical response and protection under real-life situations.[3,24,30] This is usually referred to as the electromechanical delay (EMD).[3]

The EMD has been identified as the time interval from the stimulation of the muscle by the alpha motoneuron to the first detected movement that the muscle elicits at the given joint. The EMD, as a component of the stretch reflex, is vital for both the utilization of the stored energy in the series elastic component and optimal sports performance.[24,30] Its measurement is essential for a proper understanding of how neural activation transforms to mechanical output during the execution of different movements. Several studies have identified the factors related to the duration of the EMD. This has been connected to the mechanical properties of the in-series elastic components of the muscle, the size and length of the muscle, its fiber type composition, and the presence of fatigue.[9,18,32–34] Based on these findings, changes in EMD should be expected when there are substantial alterations in the structural properties of the tendon tissue or the muscle regarding possible functional changes in excitation-contraction coupling.[15] In ACL reconstruction, specific muscle tendons are being harvested for grafts. This results in scar tissue development at the tendon,[23,26] which may affect the corresponding EMD. However, in a previous study from our laboratory, in which we examined patients with ACL reconstruction with a bone–patellar tendon–bone graft, we observed that harvesting the medial third of the patellar tendon did not significantly alter the EMD of the knee extensor muscles, as we would have expected due to the scar tissue development in the graft-harvested area.[10]

In the present study, we investigated whether this was also the case for ACL reconstruction with a quadrupled hamstring autologous graft (harvesting semitendinosus and gracilis tendons [ST/G]). Our methodology (ie, surface electromyography) allowed us to evaluate only the semitendinosus (ST) muscle and not the gracilis. In addition, we decided to investigate another major superficial muscle that belongs to the hamstring muscle group—the biceps femoris (BF). This provided us with a more general evaluation because in this fashion we included both medial and lateral hamstring muscles, even though the BF was not directly affected by harvesting. Our rationale for this inclusion was that if we found changes in the EMD of the ST, then there may also be changes in the BF, due to the fact that these 2 muscles act as a unit when the knee flexor mechanism is initiated.[1]

Therefore, the purpose of this study was to investigate the effect of harvesting the ST/G to acquire a graft for ACL reconstruction on the EMD of the knee flexor mechanism, 2 years after ACL reconstruction. We hypothesized that harvesting the ST/G tendons for ACL reconstruction surgery would not impair the EMD of the knee flexor muscles, similar to the findings in our previous study.[10]

MATERIALS AND METHODS

Participants

Twelve male patients who underwent ACL reconstruction with a quadrupled ST/G graft (mean age, 26 ± 8 years; mean mass, 74 ± 14 kg; mean height, 1.72 ± 0.10 m) and 12 healthy controls who had never suffered any kind of orthopaedic or neurologic condition (mean age, 29 ± 5 years; mean mass, 76 ± 7 kg; mean height, 1.76 ± 0.09 m) participated in the study. The controls were matched with the reconstructed patients for gender, age, height, mass, and physical activity. The participants with ACL reconstruction were tested approximately 2 years (range, 24–26 months) after the surgery. We excluded from our study patients with concomitant injuries (eg, chondral lesions, lateral collateral ligament injuries, or meniscal injuries) and patients with symptomatic anterior knee pain or objective instability at the latest follow-up examination (positive pivot-shift test results, positive Lachman test results, and arthrometer side-to-side differences of >3 mm).

Surgical Reconstruction With Hamstring Graft

All the participants were operated on by the same orthopaedic surgeon (A.D.G.). After making a 4- to 5-cm longitudinal skin incision over the pes anserinus, the surgeon performed a typical harvesting of both the ST and the gracilis tendons. The tibial tunnel was prepared with the Acufex aimer (Smith & Nephew Endoscopy, Andover, Massachusetts) set at 45° with 70° of inclination from the sagittal plane, and the knee in 90° of flexion. Subsequently, the femoral tunnel was drilled with the knee in 120° of flexion, through the anteromedial portal at the 10-o’clock position (for a right knee) or at the 2-o’clock position (for a left knee). The graft was secured at the lateral cortex of the distal femur with an EndoButton (Smith & Nephew Endoscopy) and fixed at the tibial tunnel with a bioabsorbable screw, 1 mm larger than the drilled tunnel. Finally, the graft was inspected both in full flexion and full extension so as to exclude graft impingement both at the notch and at the posterior cruciate ligament. A notchplasty was not performed in any of our cases.

Rehabilitation

All patients underwent the same rehabilitation protocol. They started from the first postoperative day with the use of continuous passive motion devices and performing sets of continuous light quadriceps muscle contractions until they were discharged from the hospital. Active exercises started during their stay in the hospital and were followed by standardized progressive rehabilitation, aiming at limiting the detrimental effects of immobilization or disuse. Rehabilitation progressed through closed kinetic chain exercises as tolerated by the patient, with the addition of pain-free open-chain exercises in safe levels, for donor-site healing. Return to sports-related activities was permitted 24 weeks after reconstruction, provided that the patients had regained full strength and stability as evaluated by isokinetic dynamometry (Biodex System 3, Biodex Medical Systems Inc, Shirley, New York), clinical tests (Lachman and pivot-shift tests, KT-1000 arthrometer [MEDmetric Corp, San Diego, California]) and functional tests (one-legged hop and crossed triple hop for distance). At the time of data collection, no clinical evidence of knee pain and effusion was found in the ACL reconstruction patients. All patients had resumed daily living functions and sports activities. All participants agreed with the testing protocol and gave their consent to participate in accordance with the institutional review board policies of our medical school.

Clinical Evaluation

Before any data collection, a clinical evaluation was performed in all participants by the same clinician (S.R.). During this evaluation, the Tegner, Lysholm, and International Knee Documentation Committee (IKDC) scores were obtained, while anterior tibial translation was evaluated using the KT-1000 knee arthrometer.[29] These measurements were performed using 134-N posterior-anterior external force at the tibia, as well as maximum posterior-anterior external force until heel clearance. Repeated anterior tractions were performed until a constant reading on the dial was registered.

Torque Measurement

For all patients, torque measurements were performed for both knees using an isokinetic dynamometer (Biodex System 3). The patients sat on the testing chair of the dynamometer and were secured with body straps, with the knee flexed at 30° and the hip joint at 30° (Figure 1A). This position was chosen to provide a hip angle and subsequently a length-tension relationship of the hamstrings approximating real-life conditions more closely than the standard 90° isokinetic testing. After warming up, all the participants were instructed to exert a maximum knee flexion as quickly and as hard as possible, after hearing a specific sound generated by the dynamometer. The individual held the maximal force until the sound was stopped. The contraction lasted for 3 seconds. Each participant performed 4 maximally explosive isometric voluntary contractions (MVCs), with a 1-minute break between contractions. The mean values of the 4 contractions were used for all comparisons between the ACL–reconstructed and the healthy contralateral knees.

Electromechanical Delay Measurement

The EMG traces were recorded from both legs simultaneously with the torque measurements, with a wireless 8-channel EMG system (Telemyo 2400T, Noraxon, Scottsdale, Arizona) and were displayed online on a computer using dedicated software (MyoResearch XP, Noraxon). Surface electromyography was obtained from the ST and BF muscles bilaterally using bipolar, circular, preamplified, pregelled Ag/AgCl electrodes with 10-mm diameter and fixed interelectrode spacing of 20 mm (Noraxon). The electrodes were attached parallel to the muscle fibers and over the dorsomedial muscle bulge at two thirds of the proximodistal thigh length for the ST, and at the dorsolateral side of the thigh at one half of the proximodistal thigh length for the BF.[22] The visually largest area of muscle belly was selected using a contraction against manual resistance. The ground electrode was placed on the medial femoral condyle. Electrodes and cables were secured with surgical tape to avoid movement artifacts. Before the placement of the electrodes, the hair of the area was shaved, and the skin was cleaned using alcohol swabs and abraded lightly with sandpaper to reduce impedance below 5 kΩ. In addition, gel was applied on the electrode surfaces to increase electrical conductivity. The participants were instructed to relax the muscles totally before a contraction trial (Figure 1B).

Before the test, all participants performed a “zero offset” function to establish a zero baseline from each of the EMG channels. The EMG signals were acquired at a sampling rate of 1000 Hz. The root-mean-square (RMS) amplitude for each muscle burst was calculated as follows: the raw EMG signals were measured in a band of 10 to 500 Hz, full-wave rectified, high-pass filtered with a Butterworth filter to remove movement artifacts with a cut-off frequency of 20 Hz, and smoothed with a 100-millisecond RMS algorithm. Measurements of the EMD were performed using the isokinetic dynamometer and the surface EMG unit, according to the protocol developed by Zhou et al.[33] Based on this protocol, the onset of torque development is defined as a 3.6-N·m deviation above the baseline level and ±15 μV deviation from the baseline for the EMG signal (Figure 2).

Statistical Analysis

A paired *t* test between the left and right sides within the control group revealed no significant differences (P = .790 for the BF and P = .208 for the ST) for the EMD; thus, the right side was selected as representative for the control group. Subsequently, a paired *t* test was performed to compare the reconstructed leg with the intact contralateral leg within the ACL reconstruction group. The right leg of the healthy control participants was finally compared with the ACL-reconstructed (ACLR) leg and the intact contralateral leg with independent *t* tests. The level of significance was set at α = .05.

RESULTS

All patients in the ACL reconstruction group were satisfied with the outcome of the surgery and resumed their preinjury level of sports activities. Negative Lachman and pivot-shift tests indicated that the knee joint stability was regained clinically for all ACLR participants. The median Lysholm score was 92 (range, 87–95), the Tegner score was 7 (range, 6–8), and the IKDC score was scaled as normal (A) at the time of examination, while for the healthy controls, the median Lysholm score was 98 (range, 96–100) and the Tegner score was 8 (range, 7–9). The KT-1000 arthrometer results revealed that the mean difference between the anterior tibial translation of the reconstructed and intact sides in the ACL reconstruction group was 1.1 mm (range, 0.5–2 mm) for the 134 N test and 1.3 mm (range, 1–2 mm) for the maximum manual test. No significant differences were found for the KT-1000 arthrometer results between the groups.

The paired *t* tests revealed that the EMD of the ACLR knee was significantly increased for both muscles (Figure 3) as compared with the intact contralateral knee. Specifically, the EMD of the ST muscle for the ACLR knee was 0.112 ± 0.037 seconds, while for the intact knee it was 0.087 ± 0.031 seconds (P = .003). The EMD of the BF muscle for the ACLR knee was 0.106 ± 0.043 seconds, while for the intact knee it was

0.083 ± 0.033 seconds (*P* = .009). Testing the ACLR knee against healthy controls also showed similar differences for the ST (0.112 ± 0.037 seconds vs 0.074 ± 0.015 seconds [*P* = .005]) and for the BF (0.106 ± 0.043 seconds vs 0.067 ± 0.016 seconds [*P* = .029]). Finally, testing the intact contralateral knee against healthy controls showed no statistically significant differences for the ST (0.087 ± 0.031 seconds vs 0.074 ± 0.015 seconds [*P* = .195]) or for the BF (0.083 ± 0.033 seconds vs 0.067 ± 0.016 seconds [*P* = .171]).

DISCUSSION

In the present study, we investigated the effect of harvesting the ST and gracilis muscle tendons to acquire an ST/G graft for ACL reconstruction on the EMD of the 2 major knee flexor muscles 2 years after the surgery. We hypothesized that harvesting these tendons for ACL surgery would not impair the EMD of the knee flexor muscles, similar with our findings in a previous study from our laboratory.[10] However, the results from this study refuted our hypothesis. We found a significant elongation of the EMD of the hamstring muscles for the ACLR knee when an ST/G graft is being used.

The same methodology used in the present study has also been used by our group to investigate the effect of harvesting the patellar tendon for ACL reconstruction on the EMD of the quadriceps.[10] In that study, we observed that harvesting the medial third of the patellar tendon did not significantly alter the EMD of the knee extensor muscles, as we would have expected due to the scar tissue development in the graft-harvested area. On the contrary, in the current study, the EMD of the ST was significantly increased, probably due to a persistent change of the biomechanical properties of the donor site. Even though an MRI evaluation from 2 of our patients, 2 years after the surgery, showed that the ST tendon was regenerated (Figure 4), it is possible that tissue development changed the material properties of the harvested muscle to a degree that resulted in EMD alterations.

Interestingly, we also found a similar increase in the EMD values of the BF, which was not directly affected by the operation. A possible explanation for this result is that the BF works synergistically with the ST during knee flexion to provide functional balance to the knee. Therefore, it is possible that we do have some neuromuscular adaptation that occurs. Several studies have emphasized the importance of neuromuscular adaptations after injury to achieve joint stability.[1,13,14] Johansson et al[13,14] suggested that joint stability is achieved by the contribution of sensory receptors to the continuous adjustment of muscle activity around the joint (co-contraction). One additional reason why we selected to examine the BF was that this muscle is an important contributor in restraining anterior tibiofemoral displacement and laterally rotating the tibia.[8] As both of these processes are implicated in the mechanism of the ACL injury, the EMD of the BF is important for evaluating the knee flexor mechanism's functional reaction during a sudden stimulus. The fact that the EMD of the investigated muscles increased in terms of the comparisons with the healthy contralateral side, as well as in comparison to healthy controls, further strengthens our explanations.

Research on knee functional adaptations after ACL reconstruction with a hamstring tendon graft has grown widely, because this technique has been increasingly advocated by many orthopaedic surgeons.[31] However, the majority of these studies have focused on evaluating hamstring strength after harvesting the hamstring tendons. Back in 1982, Lipscomb et al[19] published a retrospective evaluation of 482 cases involving either ST or ST/G harvest. Impressively, none of their subjects displayed significant loss of knee flexion strength at an average of 26 months postoperatively. Recent studies have also documented minimal or no deficits in peak knee flexion torque.[20,21] Yasuda et al[31] also reported that no significant decrease in knee flexion strength exists after the immediate postoperative period. Our study is the first study to our knowledge that documents the effect of ACL reconstruction with a hamstring tendon graft on the hamstrings' EMD. This is of great functional importance because regardless of the contractile ability of the muscles, which is depicted usually by measuring knee flexion peak torque, alterations in the EMD of the hamstrings muscle-tendon unit could compromise knee integrity or impair performance by modifying the transfer time of muscle tension to the bones.

Because EMD is determined by the elastic properties of the tendons, regeneration of hamstring tendons might be implicated with the EMD of the flexor mechanism. Radiographic and MRI studies have attempted to describe the morphologic aspect of this regeneration. Eriksson et al[5] evaluated 16 patients with MRI, 6 and 12 months after ST harvest. They observed that 12 of the 16 patients displayed radiologic evidence of

ST regeneration, in which the new tendon fused with the gracilis 10 to 30 mm below the joint line and inserted on the pes anserinus as a conjoint tendon. Similarly, we observed the same insertion and regenerative pattern in the MRI evaluation of 2 randomly selected patients from our group, 2 years after the surgery. This regeneration is often termed "lizard-tail phenomenon." Few histologic studies have been performed to assess the quality of the regenerated tissue. Eriksson et al[6] performed biopsies of hamstring tendon tissue postoperatively and compared the peripheries of regenerated ST tendons with normal tendons. The regenerated collagen fibers held the same alignment and breadth as the control tendons and exhibited uniform staining, with the exception of the appropriate forms of collagen. There were also appreciable small areas of irregularity in the collagen orientation and increased formation of fibroblasts and capillaries, indicating the presence of scar-like tissue. In addition, Ferretti et al[7] performed histologic analysis of the regenerated tissue from 3 patients at 6, 24, and 27 months after ACL reconstruction. They observed that the tendon initially (at 6 months) had a fibrous structure with fibroblastic proliferation and capillaries but few collagen fibers. However, over time (at the latter 2 time points), although the tendon had acquired quality consistent with a healthy tendon by demonstrating thicker longitudinally oriented fibers, there were small focal regions of scar tissue and irregular collagen orientation. This compositional inconsistency may alter the biomechanical properties of the reconstituted tendon. As a result, these changes may lead to differences in the stiffness of the series elastic components of tendons.

Norman and Komi[24] identified the importance of the elastic properties of the muscle in determining the duration of the EMD. They reported that the time required for the contractile component of a muscle to stretch the series elastic components is the major factor that determines this duration. On the basis of this observation, the examination of the factors that can affect the elastic properties of the tendons is essential for determining the relationship between the elasticity of the tendon and the normal muscle function. The increased EMD on the donor side medially (ST) was expected on the basis of the anatomic disturbance of the area. Our methodology comprising surface electromyography prevented us from testing the gracilis muscle. However, the ST is the stronger of the 2 donor muscles and we believe that its adaptations would not deviate from those of the gracilis. Regarding the BF, the increase of the EMD may suggest that the neuromuscular system adapts a new modified co-contraction pattern for the 2 major knee flexors. The goal of this co-contraction pattern is to protect the stability of the knee joint. Specifically, since both muscles are involved in extending the thigh and flexing/rotating the knee, it is important to act in a synchronized fashion. Thus, even though the harvesting occurred only at the medial side, the lateral side of the hamstring muscles was also affected. These results also justified our initial thought for the inclusion of the BF in the study.

As mentioned earlier, alterations in the EMD of the hamstring muscle-tendon unit could compromise knee integrity or impair performance by modifying the transfer time of muscle tension to the tibia. Vos et al[30] highlighted the importance of the EMD during physical activities. They reported that changes of the EMD might play an important role in the organization of the movement and probably result in impairment of neuromuscular control, through its relationship with the reflex time. Surely sports performance is multifactorial, but EMD, which is a component of the reflex time, is important as it affects muscle response to sudden movements during athletic activities. Late onset of hamstrings activity might also have a detrimental effect on the hamstring-quadriceps balance, possibly affecting ACL graft protection, as delayed transfer of the flexor torque may expose the graft to a possible new injury. Previous studies have showed that injury occurs within a very narrow time frame (eg, 73 milliseconds for medial collateral ligament injury).[25] Of course, it is not possible to investigate the direct connection of EMD with injury, as the latter cannot be replicated experimentally because of ethical constraints. However, the differences that we found in our study (~25 milliseconds), although small, are probably large enough to play a role in reinjury of the reconstructed knee.

Limitations in our study include the absence of a specific methodology in the literature for determining EMD and defining specific threshold levels of both signals—onset of EMG signals and force generation. Using the analog Butterworth filter introduced a time delay in the appearance of the processed EMG signals. Thus shorter EMD values were expected compared with the studies from Zhou et al.[32–34] However, our absolute values were similar to those of most studies published in the literature.[11,17,30] Nevertheless, we incorporated 2 control conditions (healthy contralateral and healthy control) and the effect of filtering applies to all conditions, creating a uniform offset of values. There are great discrepancies in the literature about the reported EMD responses to exercise. Houston et al[12] found an EMD of 41 milliseconds for the vastus lateralis preceding isokinetic concentric contractions, while Horita and Ishiko[11] found an EMD of 117.9 milliseconds for the same muscle under the same exercise conditions. This is probably due to the different types and protocols of the exercises and the techniques used to determine EMD. However, our values are in accordance with most studies, which report EMD values around 100 milliseconds.[11,17,30] Another possible limitation of our study is that our experimental design was not prospective. However, we incorporated 2 different control conditions (the intact contralateral leg from the patient group and a separate healthy matched-control group) to strengthen the case control design of our study. Furthermore, a comparative follow-up study evaluating patients with ACL reconstruction with both grafts (bone–patellar tendon–bone graft and hamstring tendons), preoperatively and postoperatively, would clearly demonstrate whether this EMD increase is mostly related to the graft source or the ACL reconstruction in general.

In addition, despite the seemingly small sample size of our experimental group, the average effect size of our significant comparisons, expressed as Cohen's *d*, was 0.94. This is considered as higher than "large" according to Cohen.[4] Effect size measures the magnitude of a treatment effect and, unlike significance tests, is independent of sample size.[4] Finally, a possible limitation of our study is the use of surface electrodes to acquire the EMD measurements. However, similar procedures have been used in previous studies[11,17,30] and are considered reliable. A strictly noninvasive methodology prevented us from directly measuring the gracilis EMG activity; however, it allowed us to satisfy the institutional review board research policies of our medical school and more easily recruit our participant populations.

In conclusion, we found a significant elongation of the EMD values of the hamstring muscles for the ACLR knee when an ST/G graft is being used. Our results suggest an impairment of neuromuscular control at the knee flexors, even 2 years after ACL surgery. However, further longitudinal investigation is required to identify how the EMD is tolerated by the central nervous system and if the increased hamstrings EMD can influence patients’ optimal sports performance and expose them to increased possibility of knee reinjury. The evaluation of the EMD during dynamic testing in high-demand activities is an interesting approach, which could also be explored in the future.

Figures

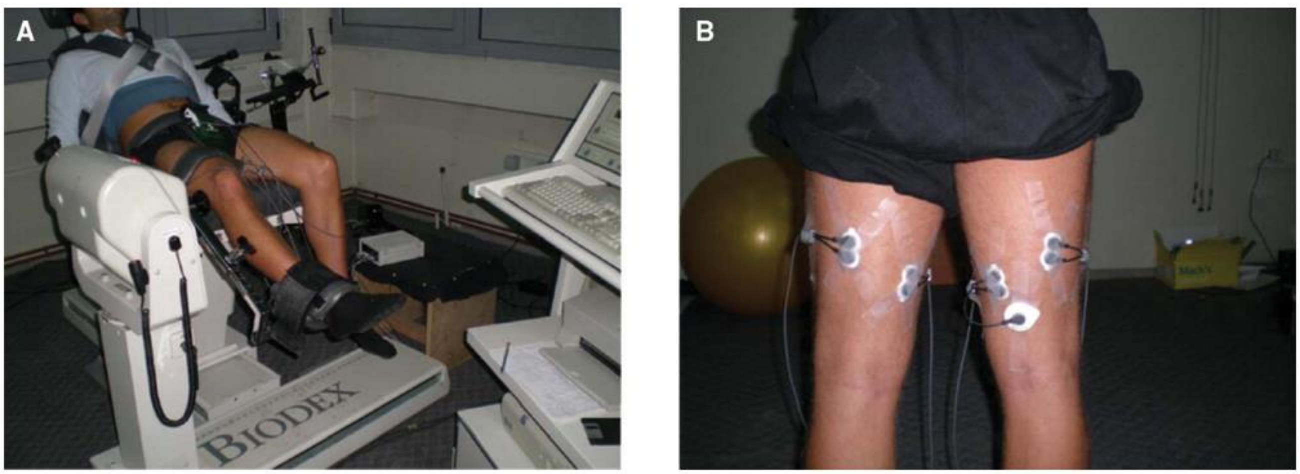

Figure 1 A, patient positioning in the isokinetic dynamometer, with the knee and hip joints flexed at 30°. B, surface electromyography was obtained from the semitendinosus (ST) and biceps femoris (BF) muscles bilaterally.

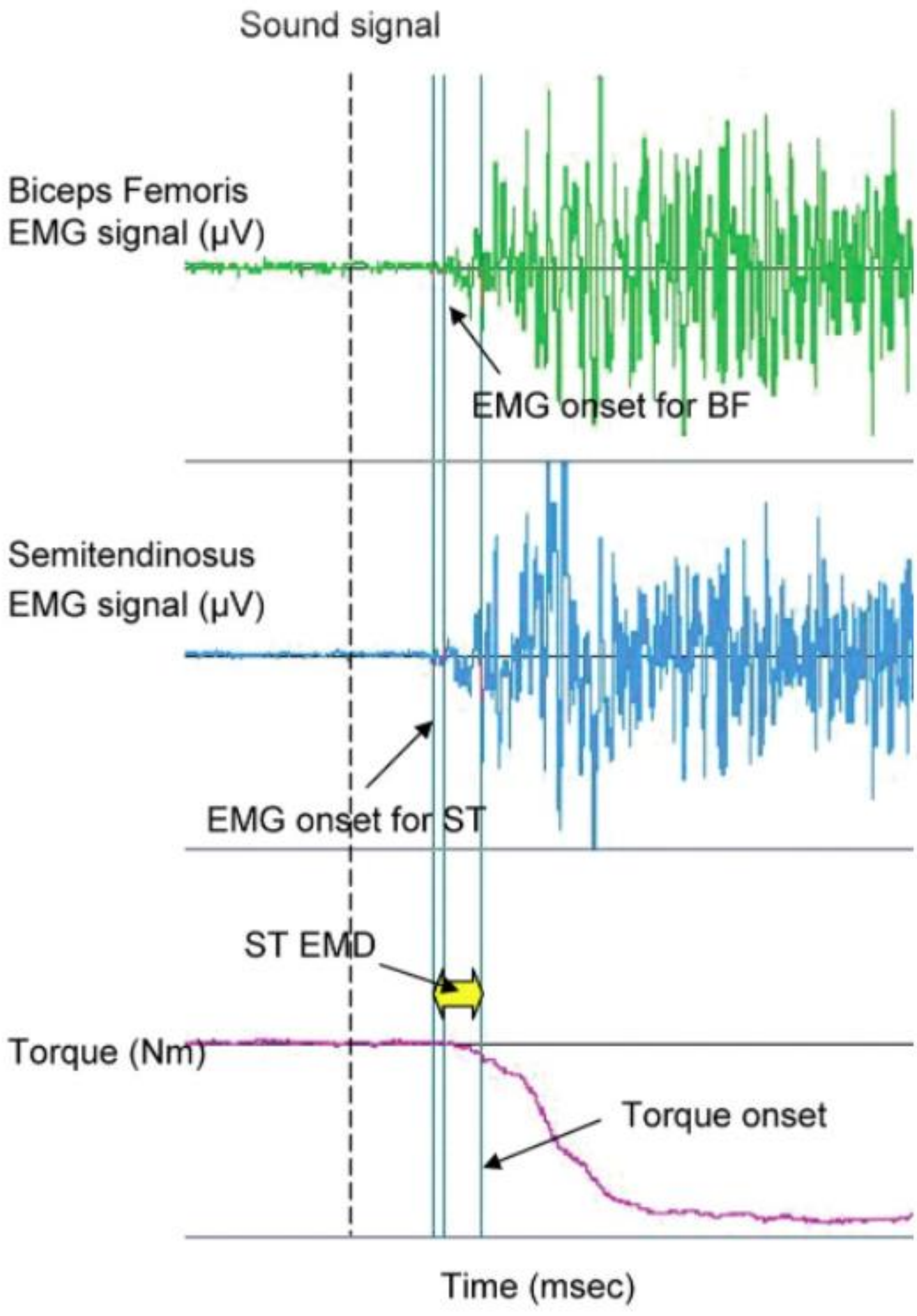

Figure 2 A typical time plot of a single trial on the presentation of the stimulus (sound signal) to the onset of the electromyographic (EMG) signal for both muscles (semitendinosus [ST] and biceps femoris [BF]) and force generation (torque). The onset of torque development is defined as a 3.6-N·m deviation above the baseline level and the onset of EMG signal as ±15 μV deviation above the baseline.

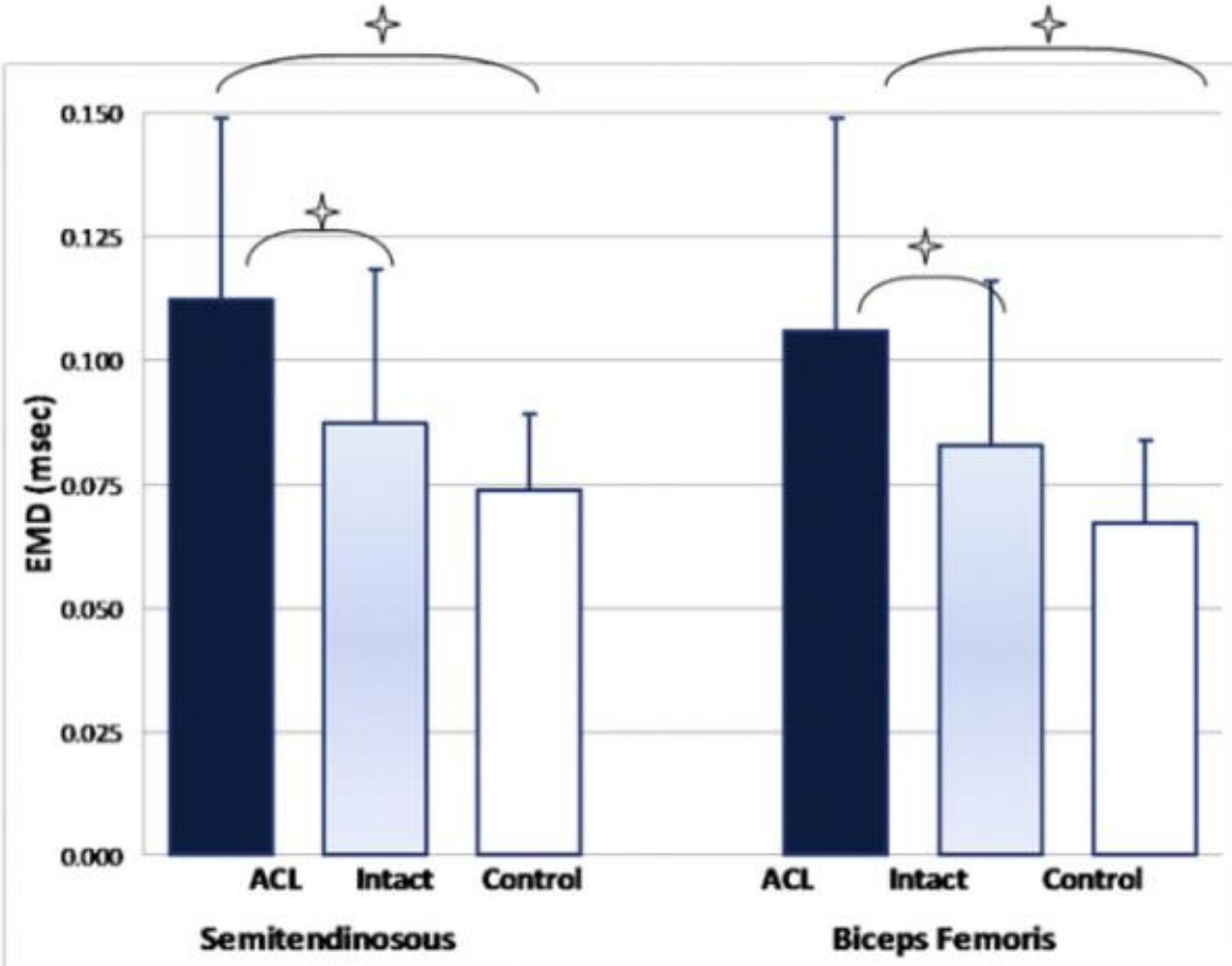

Figure 3 Group means and standard deviation values for electromechanical delay of the semitendinosus and biceps femoris muscles. Asterisks indicate the significant differences observed.

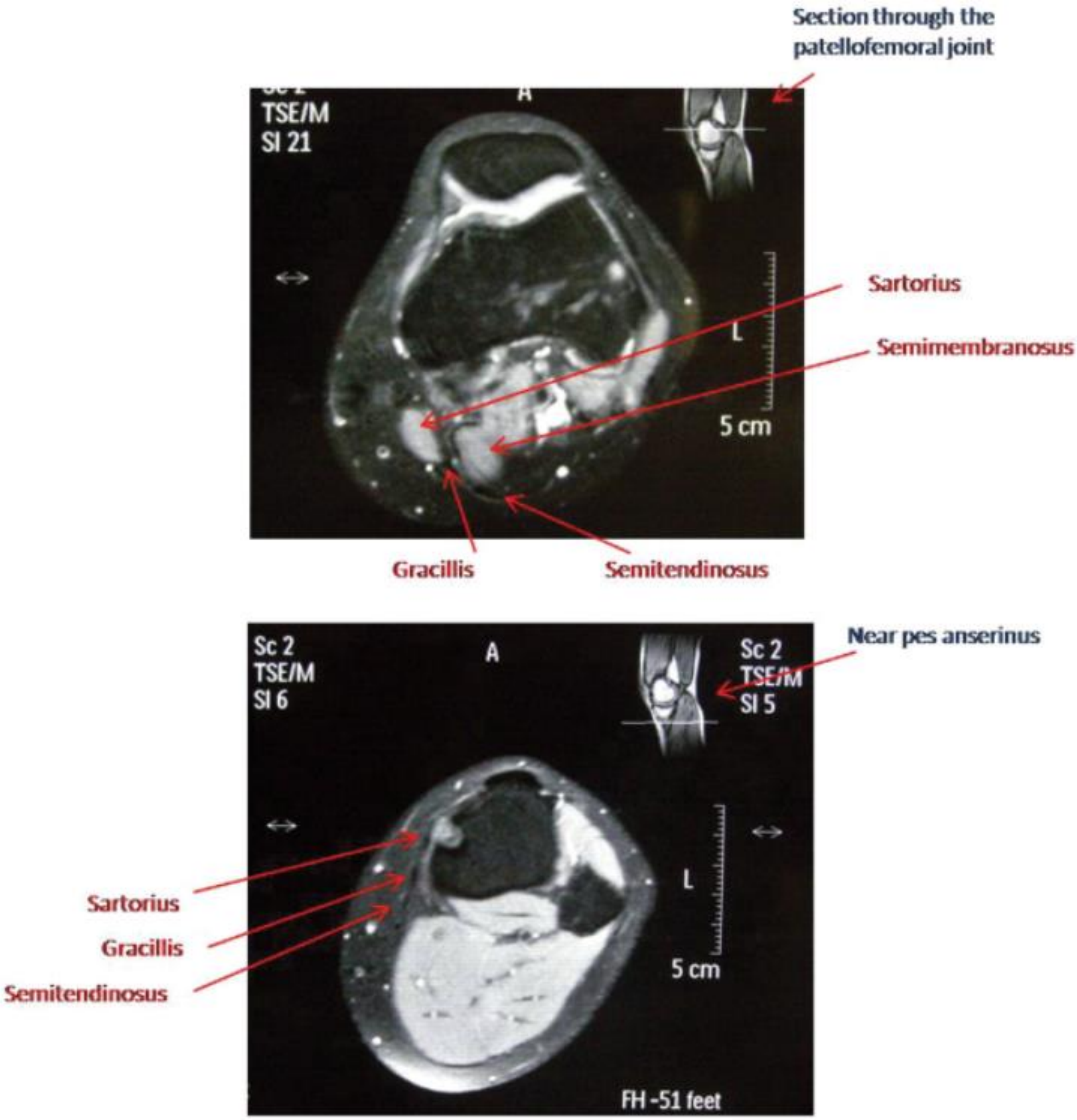

Figure 4 Postoperative MRI scans, indicating the complete semitendinosus/gracilis tendon regeneration 2 years after the surgery.

No potential conflict of interest declared.

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