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Electromechanical delay of the knee extensor muscles is not altered after harvesting the patellar tendon as a graft for ACL reconstruction: implications for sports performance

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Abstract
Although the scar tissue, which heals the donor site defect, has different elasticity from the neighbouring patellar tissue, it remains unclear if this scar tissue can lead to the changes of the electromechanical delay (EMD) of the knee extensor muscles. If such changes do exist, they can possibly affect both the utilization of the stored energy in the series elastic component, as well as the optimal performance of the knee joint movement. The purpose of this study was to investigate the influence of harvesting the patellar tendon during anterior cruciate ligament (ACL) reconstruction and the associated patellar tendon scar tissue development on the EMD of the rectus femoris (RF) and vastus medialis (VM) muscles. Seventeen patients who underwent an ACL reconstruction using the medial third of the patellar tendon were divided in two groups based upon their postoperative time interval. Maximal voluntary contraction from the knee extensors, surface EMG activity, and ultrasonographic measurements of the patellar tendon cross-section area were obtained from both knees. Our results revealed that no significant changes for the maximal voluntary contraction of the knee extensors and for the EMD of the RF and the VM muscles due to patellar scar tissue development after harvesting the tendon for ACL reconstruction. The EMD, as a component of the stretch reflex, is important for the utilization of the stored energy in the series elastic component and thus, optimal sports performance. However, from our results, it can be implied that the ACL reconstruction using a patellar tendon graft would not impair sports performance as far as EMD is concerned.

Keywords Electromechanical delay, ACL reconstruction, Sports performance, Patellar tendon, Scar tissue development

Introduction

Electromechanical delay (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 [1]. 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 [2, 3]. Several studies have identified the factors related to the duration of the EMD. It has been reported that the EMD is correlated with the mechanical characteristics of the series elastic components of the muscle, the size of the muscle and its initial length, the maximal isometric voluntary contraction (MVC) force, the muscle fiber type composition, the level of fatigue, and the percentage of fast-twitch fibers [2–13].

Vos et al. [3] highlighted the importance of the EMD during the physical activities and reported that changes of the EMD might play an important role in the organization of the movement through its relationship with reflex time. Furthermore, Norman and Komi [2] identified the importance of the elastic properties of the muscle in determining the duration of the EMD. The authors 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. To further explore these relationships, Kubo et al. [5] investigated the changes of the elastic properties of the tendon structures of the knee extensor muscles after 20 days of knee immobilization. They found a significant EMD lengthening, as a result of the increased elasticity of the muscle's series elastic components.

Apart from the changes in the stiffness of the tendons occurring due to the knee immobilization [5, 14, 15], such changes could also be a result of scar tissue development. Scar tissue is developed in the patellar tendon after harvesting either the middle or the medial part as a bone-patella-tendon-bone (BPTB) graft for anterior cruciate ligament (ACL) reconstruction. The scar tissue can lead to alterations of the tendon's elastic properties, [16–18], because it has different biomechanical characteristics [19–21]. Although the scar tissue, which heals the donor site defect, has different elasticity from the neighboring patellar tissue, it remains unclear if this scar tissue can also lead to changes of the EMD of the knee extensor muscles. If such changes do exist, they can possibly affect both the utilization of the stored energy in the series elastic component as well as optimal sports performance.

The purpose of this study was to investigate the effect of harvesting the patellar tendon and the development of the associated patellar tendon scar tissue on the EMD of the knee extensor muscles. Specifically, we hypothesized that harvesting the patellar tendon for ACL reconstruction will have an effect on the EMD of the knee extensors. The EMD was evaluated using surface EMG activity in conjunction with maximal voluntary isometric contractions. In addition, the development of scar tissue and the patellar tendon cross-sectional area was assessed using ultrasonographic measurements.

Materials and methods

Subjects

Seventeen patients who underwent an ACL reconstruction, volunteered to participate in this study. They were divided in two groups, based upon their post-operative time interval. Group A consisted of eight patients (average age: 27.25±7.95 years; height: 1.75±0.07 m; body weight: 77.62±12.12 kg), while group B consisted of nine patients (average age: 27.66±5.36 years, height: 1.80±0.07 m; body weight: 78.55±24.01 kg). The mean time interval between injury and evaluation for group A was 10.75±1.78 months, while for group B, the time interval between operation and evaluation was 45±18 months.

The separation of the patients in the two groups was based upon Moebius et al. [22]. In that study, it was identified that 0–30 months post-operatively, and especially during the first 12 post-operative months, large variations exist in the difference of the patellar tendon cross-sectional area between the healthy contralateral knee and the reconstructed knee. All patients underwent the same rehabilitation protocol, starting from the first post-operative day with the use of continuous passive motion devices, until they were discharged from the hospital. Active exercises started during their stay in hospital and were followed by standardized progressive rehabilitation. Therefore, detrimental effects of immobilization or disuse were prevented to a major degree.

Return to sports-related activities was permitted 24 weeks after reconstruction, provided that the patients had regained full functional strength and stability. At the time of data collection, no clinical evidence of knee pain was found in the ACL reconstructed subjects. All of them had resumed their daily living functions and their sports activities. Prior to any data collection, all subjects signed an informed consent approved by the University of Ioannina.

Surgical technique

All ACL reconstructions were performed using the press fit technique as described by Hertel et al. [23, 24]. All the subjects were operated by the same orthopaedic surgeon (senior author). They underwent an arthroscopically assisted ACL reconstruction using a bone-tendon-bone graft taken from the medial third of the patellar tendon. The graft was stabilized without screws in the femur and tibia by press-fit. The femoral bone block was placed with the tendon close to the over-the-top position and the tibial block was placed in a trough at the tibia so that the fibers of the ligament were parallel and tight during extension, and slightly inverted by flexion, imitating the anatomical functioning of the ACL.

Torque measurements

For all patients, torque measurements were performed for both knees using an isokinetic dynamometer (Biodex, Shirely, NY, USA). The patients sat on the testing chair of the dynamometer and were secured with body straps, while the hip and the knee joints were flexed at 90°. Measurements were obtained during maximal isometric voluntary knee extensions. All the subjects were instructed to ‘‘extend the knee against the knee attachment as hard and as fast as possible’’ after hearing a specific sound generated by the dynamometer. This sound defined the beginning of data acquisition. Moreover, patients were asked to hold their maximal effort for 3 s and until the end of the sound. Four MVCs were performed with 1 min break between each contraction. The mean values of the four contractions were used for all comparisons between the ACL reconstructed and the healthy contralateral knee.

Electromechanical delay

The method used to measure EMD has been described in detail previously [10, 11]. Briefly, using a 4-channel EMG device (Powerlab, ADInstruments, Australia) the activity of rectus femoris (RF) and vastus medialis (VM) was recorded from both legs simultaneously with the torque measurements. The EMG signal was detected by silver–silver chloride (Ag/AgCl) electrodes (inter-electrode distance of 2 cm, electrode diameter of 1 cm). The electrodes were attached parallel to the muscle fibers and over the muscle bellies. Prior to the placement of the electrodes, the hair of the area was shaved, and the skin was abraded lightly with sandpaper. Alcohol was also applied to cleanse the skin to ensure a skin resistance less than 5 kΩ. Prior to the placement of the electrodes on the skin, gel was applied on the electrode surfaces to increase electrical conductivity.

The raw EMG data were processed using a double differential amplifier (200 MΩ input impedance, 76 dB common mode rejection ratio, 10–1,000 Hz frequency bandwidth). Data collection was performed at a sampling rate of 1,000 Hz, while the filtering of the raw EMG was performed using a Butterworth filter with low and high pass cut-off frequencies of 10 and 500 Hz, respectively. Measurements of the electromechanical delay were performed using the isokinetic dynamometer and the surface EMG unit, according to the protocol developed by Zhou et al. [11]. Based on this protocol, the onset of torque development is defined as a 9.6-Nm deviation above the baseline level and ±15 μV deviation from the baseline for the EMG signal (Fig. 1).

Patellar tendon cross-section area

The patellar tendon cross-section area was examined in all patients using a standard ultrasound device with a 7.5-MHz linear transducer. The measuring of the patellar tendon cross-section area was performed with a CAD-program (AutoCAD Release 14.0) according to the method used by Moebius et. al. [22] (Fig. 2). During the ultrasonographic evaluation of the patellar tendon, the knee joint was flexed at 90° to achieve an adequate tension of the tendon. The transducer was placed above the tibia tubercle that was identified by palpation. For all the subjects, the contra-lateral knee was used as a control. All individuals with procedures on the contralateral knee or any lesion of the extensor mechanism were excluded from the study.

Statistical analysis

Differences between the healthy and the reconstructed knee for the EMD of the RF and VM muscles, the patella tendon cross-section area and the MVC torque were tested using paired samples Student's *t* tests. In addition, Pearson '*r*' correlations were conducted between: (a) the magnitude of the MVC torque and the EMD of the RF and VM muscles, (b) the time interval between the time of the ACL reconstruction and the time of the data collection with the EMD differences of the RF and VM muscles, (c) the EMD of RF and VM muscles and the patellar tendon cross-section area. Comparisons and correlations were made for groups A and B, and for all patients combined together. The level of significance was set at 0.05.

Results

In all the groups, no significant differences were found for the EMD for either the RF or the VM muscle, and for the patellar tendon cross-section area between the healthy contralateral and the ACL reconstructed knee (Table 1). Although no significant differences were found for the MVC torque between the healthy contralateral and ACL reconstructed knee for groups A and B, this variable was significant when the patients from both groups were combined.

Furthermore, no significant correlations were found in all the groups for the magnitude of the MVC torque with the EMD of the RF (group A: *r*=0.272, *P*=0.515, group B: *r*=-0.271. *P*=0.480, Combined: *r*=-0.058, *P*=0.824) and VM muscles (group A: *r*=0.338, *P*=0.413, group B: *r*=0.493, *P*=0.178, Combined: *r*=0.396, *P*=0.116), for the time interval between ACL reconstruction and data collection with the EMD differences of the RF (group A: *r*=0.408, *P*=0.315, group B: *r*=0.519, *P*=0.152, Combined: *r*=0.479 *P*=0.051) and the VM muscles (group A: *r*=0.034, *P*=0.937, group B: *r*=-0.399, *P*=0.288, Combined: *r*=-0.106, *P*=0.686), and for the patellar tendon cross-section area with the EMD of RF (group A: *r*=0.267, *P*=0.523, group B: *r*=-0.533, *P*=0.140, Combined: *r*=-0.251, *P*=0.332) and the VM muscles (group A: *r*=0.390, *P*=0.340, group B: *r*=0.208, *P*=0.591, Combined: *r*=-0.091, *P*=0.728).

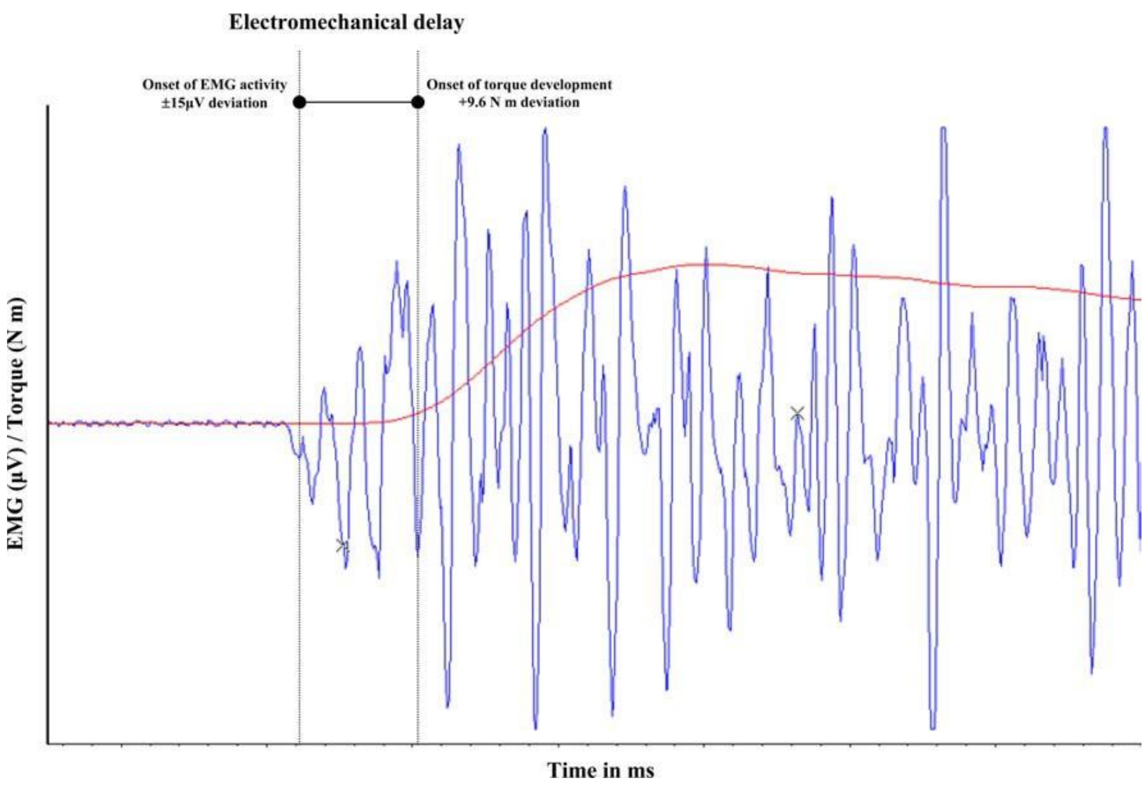

Fig. 1 An illustration of the process used to measure the EMD. The onset of torque development is defined as a 9.6-Nm deviation above the baseline level and ±15 lV deviation from the baseline for the EMG signal [11]

Discussion

Several researchers have reported that the time required for the contractile component of the knee extensor muscles to stretch the series elastic components probably amounts for the major portion of the electromechanical delay, but it is not well defined how the elastic properties affect the electromechanical delay [2, 8, 9, 12]. The harvesting of a third of the patellar tendon as a bone-patella-tendon-bone graft for anterior cruciate ligament reconstruction is a widely used surgical procedure that provides stable fixation of the bone plugs and restoration of the abnormal tibiofemoral biomechanics. However, in several studies it has been reported that the patellar donor site defect heals with scar tissue, which has similar histological characteristics but different elastic properties with the original tissue [19, 20]. Therefore, it is possible that such a patellar tendon, with altered elastic properties due to scar tissue development, may lead to differences in the stiffness of the series elastic components of the knee extensor muscles.

However, our results indicated that scar tissue development does not seem to change the stiffness of the patellar tendon in a level that could result in EMD alterations. We found no significant differences in the EMD of the RF and the VM muscles for our ACL reconstructed patients. In addition, no significant differences were found even when the patients were examined separately and based on the post-operation time interval. Therefore, it can be concluded that the scar tissue cannot produce significant changes in the time required for the contractile component to stretch the patellar tendon of the knee extensor muscles. Furthermore, scar tissue development seems to result in different alterations than knee immobilization, where Kubo et al. [5], found that the decrease of stiffness of the tendon structures could prolong the EMD of the knee extensor muscles. This is in accordance with the findings of Kaneko et al. [25] who reported that peripheral physiological alterations can prolong the EMD in ACL reconstructed knees with intact patellar tendon and atrophied quadriceps muscle.

Kubo et al. [5] also found that 20 days of knee immobilization can result in a significant decrease of the knee extensors torque. This decrease was related with the duration of the EMD. In our study, we did not find such a correlation, even though the operated knee

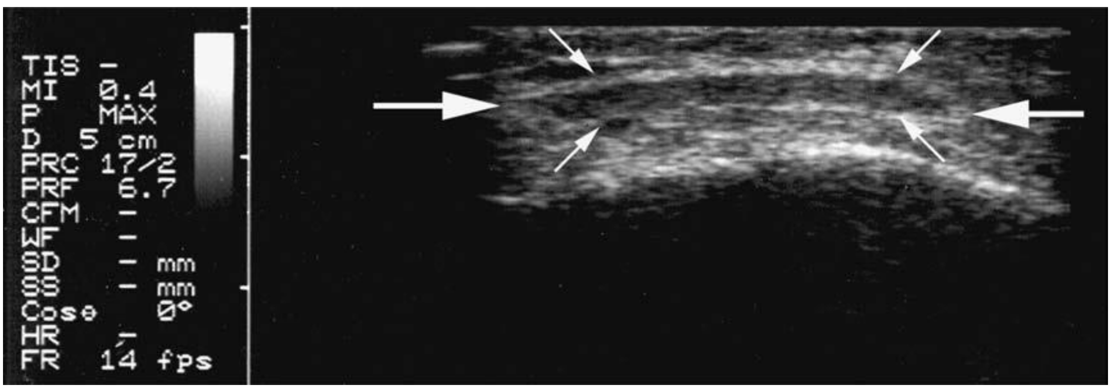

Fig. 2 Ultrasound image where arrows indicate the limits of the cross-section area of the patellar tendon

showed a significantly reduced extensor torque in comparison with the healthy contralateral knee when patients were combined. In addition, in ACL reconstructed patients a possible destabilizing effect of the patella will not be the result of changes in the EMD of the VM muscle, since Yeung et al. [10] reported that an altered EMD in VM would affect the stabilizing effect of the patella during knee extension.

No significant differences were found between the reconstructed knee and the contralateral healthy knee for the size of the patellar tendon cross-section area (Table 1). In addition, no relationship was found be- tween the size of the patellar tendon cross-section area and the duration of the EMD in all groups and for both knees. Thus, it can be mentioned that neither the cross-section area of the surgically affected patellar tendon nor the area of the healthy tendon of the contralateral knee are related with the duration of the EMD.

Clinically, alterations in the EMD of the quadriceps muscle-tendon unit could compromise knee integrity or impair performance by modifying the transfer time of muscle tension to the tibia. Vos et al. [3] 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. Our findings showed that using the medial third of the patellar tendon as a donor site for ACL graft did not affect the EMD of the extensor muscles. Therefore, ACL reconstruction does not seem to affect sports performance in terms of EMD alterations of the extensor muscles.

Table 1 Group results of the patellar tendon cross sectional area, EMD measurements, and MVC knee extensor torques

	operated knee		Contral-lateral knee		Difference	Difference (%)	*P* value
	Mean ± SD	Range	Mean ± SD	Range			
Area of the patellar tendon (cm^2)							
All patients (group A and B)	1.42 ± 0.40	(0.64–2.65)	1.24 ± 0.40	(0.61–2.13)	0.22	17.74	0.055
Group A	1.26 ± 0.50	(0.64–2.27)	1.13 ± 0.37	(0.61–1.76)	0.13	11.50	0.409
Group B	1.70 ± 0.68	(0.75–2.65)	1.38 ± 0.42	(0.82–2.13)	0.32	23.18	0.089
EMD of RF muscle (ms)							
All patients (group A and B)	57.01 ± 12.89	(34.50–82.00)	58.94 ± 11.96	(31.75–81.50)	−1.92	−3.26	0.493
Group A	56.34 ± 10.10	(32.75–63.75)	54.31 ± 10.20	(34.50–67.25)	2.03	3.73	0.281
Group B	57.61 ± 15.56	(31.75–81.50)	63.05 ± 12.43	(46.75–82.00)	−5.44	−8.63	0.287
EMD of VM muscle (ms)							
All patients (group A and B)	57.52 ± 11.72	(31.75–81.50)	57.17 ± 11.10	(34.50–82.00)	0.35	0.61	0.912
Group A	59.50 ± 9.64	(50.75–80.50)	59.90 ± 7.11	(48.25–70.25)	−0.40	−0.67	0.925
Group B	55.77 ± 13.63	(35.00–76.25)	54.75 ± 13.72	(40.75–82.50)	1.03	1.88	0.840
Mean torque of the MVC (Nm)							
All patients (group A and B)	155.14 ± 50.18	(60.20–261.20)	180.39 ± 49.08	(62.48–255.13)	−25.25	−13.99	0.018*
Group A	149.23 ± 53.23	(90.58–261.20)	176.09 ± 36.50	(133.60–243.43)	−26.86	−15.26	0.052
Group B	160.39 ± 49.90	(60.20–213.18)	184.21 ± 60.15	(62.48–255.13)	−23.81	−12.92	0.166

*Significant difference at the 0.05 level

In the present study, isometric testing was used in contrast to dynamic protocols performed in previous studies [1, 2, 4]. This was done because our purpose was different, since we focused on testing how the post-operative scar on the patellar tendon affects the time required for the transfer of quadriceps tension to the tibia. Thus, to ensure validity and accuracy, it is necessary to control the tension of the elastic elements of the muscle-tendon unit. Strict isolation of the patellar ten- don tension can be achieved with the knee flexed to a certain angle. Additionally, this should be done preferably to an angle of maximum patella stabilisation into the trochlea. For this reason, we tested EMD isometrically, at 90° of flexion, which has been the preferred knee position for similar testing protocols in the literature [12, 13]. Dynamic testing in high demanding activities is an interesting approach which could be a future direction for our related research, provided that significant side-to-side differences were measured. In addition, future studies should explore the effect of different strength training rehabilitation protocols on the stiffness of the patellar tendon and the duration of the EMD [26, 27].

Obviously, further investigation is required to identify how the EMD is tolerated by the central nervous system. It seems that total reaction time in MVC, secondary to a visual stimulus, will not be altered due to EMD change since the scar tissue development in patella tendon does not alter the duration of the EMD. On the other hand, the EMD may simply represent an event driven by the structural properties of the skeletal muscle that is fundamentally ignored by the central nervous system.

In conclusion, the scar tissue, which is developed in the donor site defect of the patellar tendon after harvesting the medial third, does not significantly alter the EMD of the knee extensor muscles. Furthermore, any MVC knee extensor strength deficit found in the ACL reconstructed patients, does not produce any significant changes in the EMD. The EMD, as a component of the stretch reflex, is important for both the utilization of the stored energy in the series elastic component and thus, optimal sports performance. However, from our results, it can be implied that ACL reconstruction using a patellar tendon graft would not impair sports performance as far as EMD is concerned.

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