Original Paper

Muscle Strength and Geometrical Changes in a Paralysed Muscle Following FES

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Abstract: This study proposes the application of a strengthening index to quantify the effect of training, by functional electrical stimulation (FES), on the force capacity of the quadriceps in spinal cord injury (SCI) subjects. The index is based on evaluating the average muscle force per unit area. This measure is shown to express the overall increase in the muscle force capacity, while accounting for the changes taking place in muscle geometry. The proposed index is demonstrated on one subject with SCI, on whom a longitudinal follow-up was conducted. The measurements included the knee extension torque, from which the force in the quadriceps muscle was evaluated. Additionally, *in vivo* magnetic resonance imaging of the thigh was used to obtain the muscle anthropometry. In the training period followed-up in this study, the average force per unit area was found to increase from 27 N/cm^2 in the pretrained muscle to 40 N/cm^2 after eight weeks of training by FES. The major increase in the physiological cross-sectional area of the muscle took place during the first four-week period; 12% of the total 13.5%. Conversely, only a minor change in the average force per unit area of the muscle was observed during the first four weeks of training (28 N/cm^2 at the end of the fourth week). Thus, the major increase (43%) in the ratio of peak force to muscle physiological cross-sectional area was observed during the second four-week period of training. This latter response is attributed to neural adaptation of the axons and neuromuscular junction rather than to an increase in the muscle fibre specific tension.

Key words: spinal cord injury, functional electrical stimulation, strengthening index

Introduction

To design a functional electrical stimulation (FES) training protocol by which a desired outcome can be achieved, the effects of electrical activation on the trained, paralysed muscle need to be studied. Following spinal cord injury (SCI), paralysed muscles suffer from atrophy and their fibres transform into type II fast-fatigable fibres [1, 2]. Under such circumstances, the muscle fibres can only generate a limited amount of force and they tend to tire rapidly [3]. However, when chronic electrical stimulation is applied to the paralysed muscles of patients with upper motor neuron lesions, these changes can be reversed [4]. Chronic electrical stimulation has been shown to be effective not only in building muscle strength, but also in improving fatigue resistance [5, 6]. It should be emphasized, though, that the improvement in the muscle goes into decline if FES training is discontinued [7].

Hypertrophy of the thigh muscles of paraplegics subjected to FES involves an increase in both the diameter and the total number of fibres and, consequently, in the cross-sectional areas of the entire muscle [4, 8]. The effect of training by FES also involves histochemical changes demonstrated by an increase in the oxidative capacity of the myofibrils [4, 9–11]. The changing condition of the muscle during electrical stimulation with regard to the modification of structure, geometry and function, clearly should be taken into consideration wherever muscle behaviour is being studied and modelling is attempted. For instance, force/electro myography(EMG) and/or force/metabolites relations depend on the training status of the muscle [4, 9, 12, 13]. Despite the fact that the above factors have been used to evaluate muscle conditioning in subjects with SCI during and following training by FES, it is widely believed that muscle strength and muscle fatigability should be

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considered as additional important criteria to assess functional rehabilitation in individuals [7, 14–17].

The main goal of the present study was to suggest an objective measure by which the functional changes in the muscle following training by FES can be estimated. Strengthening involves an increase in the muscle force. Since an increase in the dimensions also takes place, a specific index should be established to account for the overall effect of training on the muscle force capacity. The strengthening index proposed in this study is the average muscle force per unit area and, as will be later shown, this index can express the changes taking place within the muscle. Attention should be paid, though, to the distinction between average muscle force per unit area and muscle specific tension. Whereas the latter reflects an inherent capacity of the muscle fibre, the former is an outcome of several neuromuscular factors, among which are plasticity of the neuromuscular junction and fibre composition of the muscle. It should be noted that evaluation of the average muscle force per unit area requires accurate information on the muscle anthropometry (ie, cross-sectional area and moment arms). For that, we make use in this study of *vivo* magnetic resonance imaging (MRI) measurements, in conjunction with biomechanical measurements.

Subjects and Methods

The proposed measure is demonstrated on one subject, using previously published protocols of stimulation and methodologies of training and strength testing.

Subject

The subject had a complete, spastic, paralysis at the T10 level and was 52 years of age when FES was first applied. The time from injury to first FES was four months. Spasticity was of the tonic type, characterized by overall extension patterns and was elicited upon onset of electrically evoked contractions or during transfer of the subject. The subject was generally in good health and was not given any treatment other than FES during the study period.

Stimulation

Stimulation was transcutaneous, from a constant-current programmable stimulator, providing monophasic pulse trains [18]. The current intensity for supramaximal stimulation was determined from the isometric recruitment curve (IRC), as the current above which the torque curve levelled off. For the studied subject, the current intensity was 140 mA. The IRC was tested again in the middle and at the end of the training period and was found to be similar to the initial reading. The other stimulation parameters—frequency of 20 Hz and pulse width of 0.25 ms—were kept unchanged throughout this study. The stimulation electrodes used were rectangular, 4 x 5 cm, and were made of silicon rubber. To determine the location of the muscle motor points a supramaximal stimulation was applied for 10 seconds to the muscle and the isometric knee torque was recorded online . The placement of the positive electrode was then slightly relocated and stimulation was repeated. The response to the stimulus was maximal when the positive electrode was placed at 8 cm distal to the inguinal area, over the rectus femoris belly and the negative electrode was placed 5 cm proximal to the patella. Five minutes of rest were allowed between two adjacent tests to minimize any effects of fatigue or post-tetanic potentiation. The above tests were made separately from any other FES induced activities. Once the electrode location for any given subject was established, a surgical marker was used to indicate the exact locations on the skin so that they could be accurately repositioned during the different testing days. Three additional pairs of electrodes were used for the training protocol: one pair to stimulate the left (contralateral) thigh muscle (placed similarly to those of the right thigh) and two pairs (one for each leg) to evoke the flexion reflex. For these latter pairs, the positive electrode was placed 5 cm lateral to the tibial tuberosity and the second (negative) electrode was placed 5 cm distal to the first (Fig. 1).

Training protocol

The training protocol was similar to previously used and

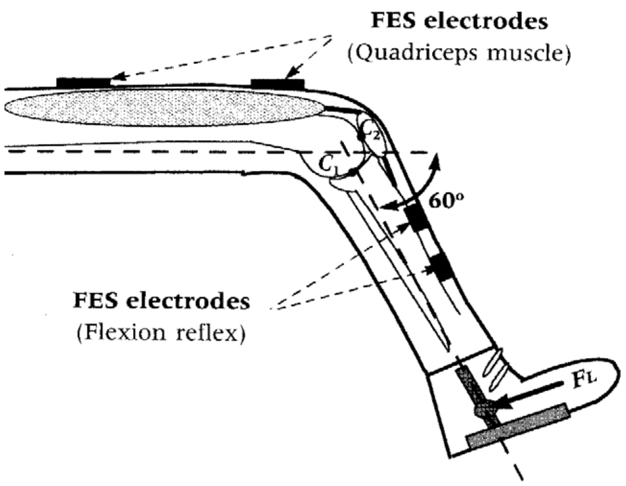

Fig. 1. Structural schema of the lower extremity, where the quadriceps muscles are being stimulated, indicating arrangement of functional electrical stimulation(FES) electrodes on the patient's leg, and tibiofemoral (C_1) and patellofemoral (C_2) contact points. F_L is the recorded force at the ankle level. The measurements were taken under isometric conditions with a knee flexion angle of 60°. The moments exerted by the gravity force of the shank and the passive ligament forces about the tibiofemoral joint (contact point C_1) of the knee were compensated for, prior to stimulation, by setting the load cell reading (F_L) to zero.

published protocols [12, 18] and included two weekly FES sessions, 45 minutes each, of sequential submaximal isotonic activation of the quadriceps of one leg and elicitation of the flexion reflex of the hip and knee of the opposite leg. During training, the subject's thigh was supported horizontally to his wheelchair, with his lower leg free to extend about the knee joint from an initial knee flexion angle of approximately 60°. Full extension of the knee for 4 seconds, obtained by a 120 mA stimulation of the quadriceps, was followed by a 4 second flexion by a 70 mA stimulation of the flexion reflex.

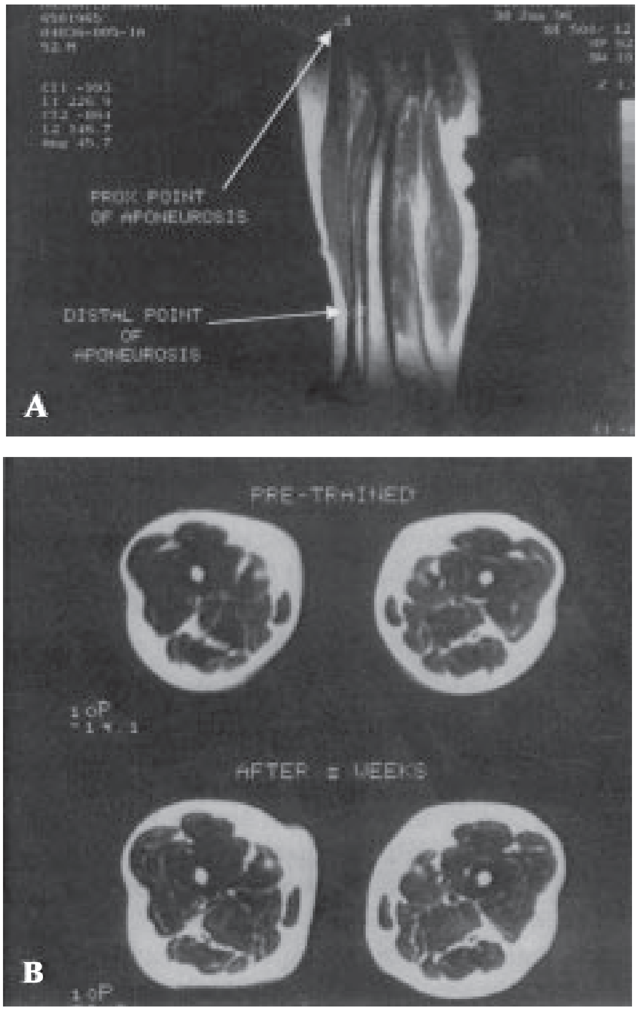

Fig. 2. A) T1-weighted longitudinal (sagittal) image of the thigh. Proximal (top) and distal (bottom) points of aponeurosis are shown. B) T1-weighted axial image of the mid-thigh illustrating muscles before and after eight-weeks training.

Isometric strength tests

The strength tests were made on the right leg according to previously published methodologies [19]. Briefly, they were made in the sitting position at a knee flexion angle of 60° and were taken under isometric, supra-maximal, continuous contraction of 180 seconds. The subject's thigh was supported and belted horizontally to the seat, while the lower leg was fixed at the level of the ankle to a rigid fixture through a load cell (Fig. 1), by which the resulting torque was measured and on-line digitized at 2,000 samples s^{-1}. To ensure unfatigued initial conditions of the muscle, each test was made at the beginning of the training session, before any electrically induced activation took place.

Acquisition of MRI data

Data on the anthropometry of the quadriceps heads and the knee joint were obtained *in vivo* from MRI measurements at knee flexion of 0°, and were collected on a whole body MR imager (Elscint Gyrex V 0.5-T system, Elscint, Haifa, Israel). Standard soft tissue MRI protocols (T_1-weighted) were used to generate a series of axial 15-mm slices with 6-mm interslice gaps and sagittal 10-mm slices with 4-mm gaps contiguous cross-sectional within a field of view of 500 x 500 mm. Four excitations were averaged, using the spin-echo technique with 500 ms repetition time and 12 ms echo time. The subject was instructed to lie supine with the hips extended and to remain motionless for the duration of the scan. Data were acquired on a 167 x 200 matrix and images were reconstructed on a 256 x 256 matrix. The images were analyzed using a built-in 'irregular region of interest (IRROI)' area measurement programme of the Gyrex Viewing System (GVS), the Elscint image viewing and processing module. A series of contiguous axial images of the thigh were acquired from the plane of the greater trochanter to the plane of the condyle of the femur. In calculating the cross-section area (CSA) of muscles on the GVS, the cursor was used to exclude neurovascular structures, accumulations of fat, and fibrous tissue bundles that were clearly delineated from the muscle groups. The relative orientation between the longitudinal axes of the thigh muscle and the image frame was calculated, enabling evaluation of the CSAs of the muscles perpendicular to their longitudinal axis. Images of the axial and longitudinal (sagittal) slices of the thigh are shown in Figure 2. Since in some cases it was not possible to accurately distinguish between the individual muscles of the vasti (particularly the vastus intermedialis), this muscle was divided into two sub-groups: lateral bulk (VL) that includes the vastus lateralis and the lateral half of the vastus intermedialis, and medial bulk (VM) that includes the vastus medialis and the medial half of the vastus intermedialis; placed, respectively, laterally and medially to the sagittal plane of the femur (Fig. 3). A serial of axial contiguous CSAs of the thigh muscles including the rectus femoris (RF), and the VL and VM bulks of the vasti group were obtained from each of the predetermined serial of axial slices.

Muscle geometry

The muscle CSAs derived from each of the axial images were then curve-fitted, using the least squares (LSQ) polynomial regression method, to interpolate the muscle

CSA versus the distance x from the proximal point of aponeurosis (Fig. 3). Analysis of variance was used to determine the adequate order of the polynomial. By comparing the estimated values of the residual sum of squares for the polynomials of the second to the sixth order, a polynomial equation of order four was selected. The volume of the muscle (V_M) was evaluated by integrating the area over the distance from proximal to distal aponeurosis (Fig. 3). The physiological cross-sectional area was estimated by dividing muscle volume V_M by muscle length l_M. The procedure was repeated for each of the above mentioned quadriceps heads, including: the RF, and the VL, and VM bulks of the vasti muscles.

Quadriceps force

The lower extremity was modelled as three rigid segments: thigh, patella, and shank (this last including the foot). The knee was represented as a two-joint system: the tibiofemoral joint and the patellofemoral joint, referred to in Figure 1 by their respective contact points C_1 and C_2 [20–22]. Under isometric conditions, moment equilibrium of the system of forces acting on the patella about the patellofemoral contact point C_2 enables us to derive a mathematical relation between the patellar tendon force (F_{PT}) and the quadriceps tendon force (F_{QT}). Likewise, moment equilibrium of the system of forces acting on the shank about the contact point C_1 enables us to calculate F_{PT} from the measured external force F_L. For these calculations it is however necessary to know the moment arms.

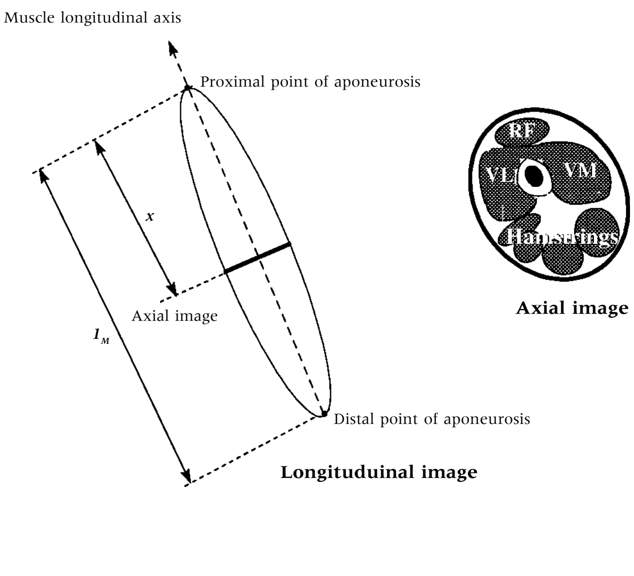

Fig. 3. Schematic description of the longitudinal and axial images of the thigh. The longitudinal image (left) depicts the muscle length L_M, and the distance x, from the proximal point of aponeurosis to a given axial image. The axial image (right) shows the rectus femoris (RF) head, lateral (VL) and medial (VM) bulks of the vasti muscles and the hamstrings muscles.

Moment arms of the muscle

The method used to measure the moment arms was adapted from Wretenberg et al [23]. Data were measured *in vivo* using MRI and were taken from the sagittal images at 0° knee flexion. The centre of the contact area between the femur and the tibia (tibiofemoral contact point) and between the femur and the patella (patellofemoral contact point) were identified from slice images of the knee at the sagittal plane (not shown in Fig. 2). The line connecting the proximal and distal insertions between muscle and tendons were drawn and the line of action of each muscle was identified. The moment arm of each muscle was taken as the perpendicular distance from the contact points to the line of action. The patellar tendon moment arm, r_3, corresponding to the tibiofemoral joint (contact point C_1), and the ratio between the moment arms of the quadriceps tendon, r_1, and the patellar tendon, r_2, corresponding to the patellofemoral joint (contact point C_2) were then evaluated. To obtain the values at 60° flexion, r_3 and the ratio r_1/r_2 were scaled, based on the data provided by Nisell [20]. The quadriceps moment arms are summarized in Table 1.

Results

Changes in muscle geometry

The shape functions corresponding to the cross-sectional area of the muscle $A_M(x)$ with the 95% confidence limit are shown in Figure 4 for the RF, and the VL and VM bulks of the vasti group. The pretrained condition is represented by dark circles and a dashed line and the eight-week trained condition by open squares and a solid line. It is noted that the major geometrical changes of the muscle following training are observed in the region of the muscle belly of the RF head. The variations, over the training period, of the cross-section area at the belly region of the RF head and the lateral and medial bulks of the vasti muscles are demonstrated in Table 2. After the first four weeks of training, the cross-sectional area at the belly region of the RF head was shown to increase by about 10%. A further increase of 11% in this area was observed during the next four weeks of training. Only minor variations in the cross-sectional area were observed in the belly regions of the VM and VL where changes were less than 4% over the entire training period (eight weeks).

Tables 3 and 4 present, respectively, the volumes and physiological cross-sectional areas (PCSA) of the RF head and the VM and VL bulks of the right quadriceps: before training and after the first four weeks and second four weeks of training by FES. During the first four weeks, training resulted in a major increase of more than 8% in volume (from 136 cm^3 to 147 cm^3) and PCSA (from 4.9 cm^2 to 5.3 cm^2) of the RF head. The increase observed over the same training period for the VM and VL were, respectively, 4.3% and 5.3%. During the

Table 1. Values of the moment arm r_3 of the patellar tendon corresponding to the tibiofemoral joint (contact point C_1) and of the ratio r_1/r_2, between the quadriceps tendon moment arm (r_1) and the patellar tendon moment arm (r_2) corresponding to the patellofemoral joint (contact point C_2). The values are given for 0° knee flexion angle magnetic resonance imaging (MRI) data and for 60° knee flexion angle after scaling (Nisell [20]).

Moment arm	0° flexion (MRI)	Scaling factor (Nisell [20])	60° Flexion (estimated)
r_3	35.2 mm	1.25	44.0 mm
r_1/r_2	2.19	0.73	1.61

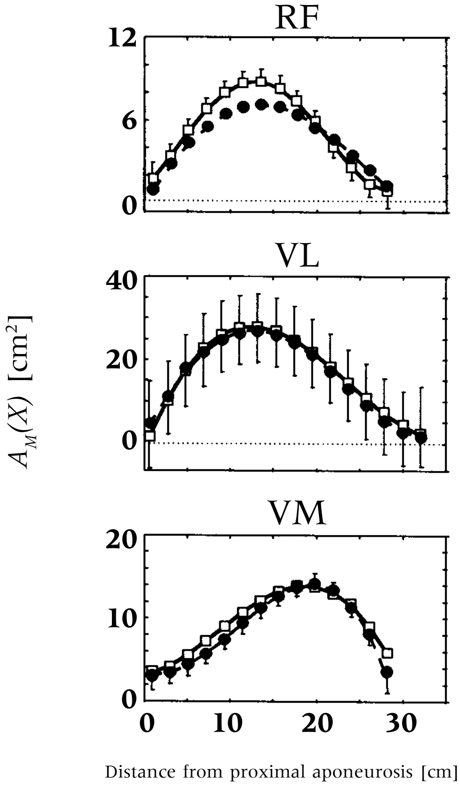

Fig. 4. Shape function with 95% confidence boundaries of the pretrained (●) and eight weeks trained (□) quadriceps. Muscles of the right quadriceps are shown as follows: rectus femoris (RF), head and the lateral (VL), and medial (VM) bulks of the vasti muscles.

second four weeks of the training period, ie, from the end of the fourth week to the end of the eighth week, the volume and PCSA of the RF head increased by less than 2% and those of the VL bulk decreased by almost 3%. The VM bulk hypertrophied by almost 10% over the same period of training. Over the entire training period, i.e., from the beginning of the first week to the end of the eighth week, the hypertrophy was 2% for the VL and 14% for the VM. The RF head, over which belly the FES electrodes were placed, hypertrophied by only 10%. The training (i.e., after eight weeks) was 6.4% (from 839 cm^3 before training to 893 cm^3 after eight weeks) and the overall increase in PCSA over the same training period was 13.5% (from 28.2 cm^2 to 32.0 cm^2).

Changes in muscle mechanical output

Figure 5 shows curves of the knee torque during the first 10 seconds of isometric supramaximal contraction of the quadriceps. Typically, the ascending phase of the activated quadriceps lasted 8 to 10 seconds after which the torque levelled off. The curves shown in Figure 5 were recorded from the pretrained quadriceps, and at the end of the

Table 2. Variations of the cross-sectional area at the muscle belly of the rectus femoris (RF) head and the medial (VM) and lateral (VL) bulks of vasti muscles over the functional electrical stimulation training period.

	Pretrained (cm^2)	End of first 4 weeks (cm^2)	End of second 4 weeks (cm^2)
RF	7.15	7.9	8.8
VM	14.2	13.8	13.8
VL	27.0	27.3	28.0

Table 3. Variations of the volumes of the rectus femoris (RF) head, medial (VM) and lateral (VL) bulks of the vasti muscles and the volume of the entire quadriceps group (Quads) over the FES training period.

	Pretrained (cm^3)	End of first 4 weeks (cm^3)	End of second 4 weeks (cm^3)
RF	136	147	149
VM	210	219	240
VL	493	519	504
Quads	839	885	893

first and second four-week periods of training. The calculated peak force in the quadriceps is indicated for each curve. In the first four-week period, training resulted in an increase of 18% of the peak force of the quadriceps (from 760 N at first FES to 900 N at the end of the fourth week). Substantial improvement in the quadriceps force generation capacity occurred during the second four-week period of training whereas its peak force increased by 42% (up to 1280 N at the end of the eighth week).

Table 4. Variations of the physiological cross-sectional areas of the rectus femoris (RF) head, medial (VM) and lateral (VL) bulks of the vasti muscles and the physiological cross-sectional areas of the entire quadriceps group (Quads) over the functional electrical stimulation training period.

	Pretrained (cm^3)	End of first 4 weeks (cm^3)	End of second 4 weeks (cm^3)
RF	4.87	5.27	5.35
VM	7.52	7.83	8.61
VL	17.6	18.5	18.0
Quads	28.2	31.6	32.0

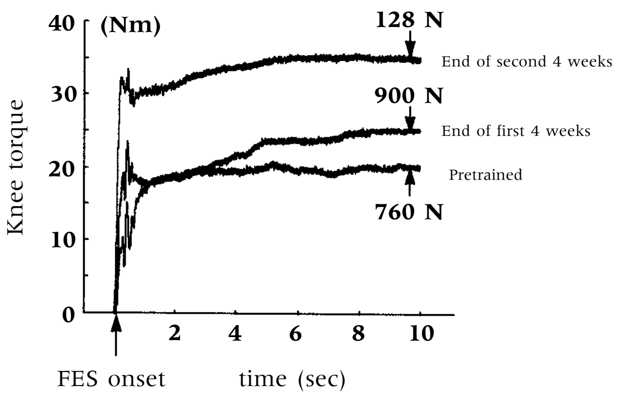

Fig. 5. Knee-torque curves from the pretrained quadriceps muscle and at the end of the first and second four weeks of training by functional electrical stimulation(FES). The onset time of FES and the maximal measured knee torque $M_K(max)$ are designated by arrows. The corresponding maximal quadriceps force $F_{QT}(max)$ is indicated for each curve.

Changes in muscle average force per unit area

The cumulative effect of the eight weeks of training by FES on the quadriceps group is summarized in Table 5. The estimated average force per unit area in the pretrained quadriceps was 27 N/cm^2 [$F_{QT}(max)$ = 760 N; PCSA = 28.2 cm^2]. Following the first four weeks of training the estimated average force per unit area increased by only 3.7% (28 N/cm^2), whereas, the peak force levelled at 900 N and the PCSA increased to 31.6 cm^2. A substantial improvement in the force generation capacity of the quadriceps was obtained during the second four-week training period, where the average force per unit area increased by 43%, from 28 N/cm^2 to 40 N/cm^2 [$F_{QT}(max)$ = 1280 N; PCSA = 32.0 cm^2].

Discussion

The purpose of the present study was to quantify the combined mechanical and geometrical changes in a paralysed skeletal muscle following training by FES. The method presented here is formulated to evaluate the average muscle force per unit area, since this measure can represent strengthening as expressed by the increase in muscle torque, while accounting for muscle hypertrophy. Thus, studying the overall changes of the paralysed muscle provides a better insight into the force producing capacity and adaptation of the neuromuscular system that follows training by FES. Strengthening of paralysed quadriceps in the course of training generally results in an increase of the produced peak force, accompanied by hypertrophy of the muscle.

The proposed measure was demonstrated in detail on one typical subject with SCI. For this subject, it was shown that by applying FES over a training period of eight weeks, it is possible to improve the knee extension torque by almost 70%. This is in correspondence with previously published results obtained from a larger group of SCI subjects [16]. In the present study, conducted over a similar training period as this latter study, the

Table 5. Changes in the maximal knee torque $M_K(max)$, maximal quadriceps force $F_{QT}(max)$, quadriceps physiological cross-section area (PCSA), and muscle average force per unit area, before training, and after the first four weeks and second four weeks of training.

Training period (weeks)	$M_K(max)$ (Nm)	$F_{QT}(max)$ (N)	PCSA (cm^2)	Muscle average force per unit area (N/cm^2)
Pretrained	20.7	760	28.2	27
End of first 4 weeks	24.7	900	31.6	28
End of second 4 weeks	35.0	1,280	32.0	40

average muscle force per unit area increased by 48% (from 27 N/cm^2 to 40 N/cm^2). The estimated values of the average muscle force per unit area obtained in our study ranged within the expected values reported in the literature [24–27]. While using computed tomography to determine the cross-sectional area of the elbow flexors, Nygaard et al have shown that the average force per unit area was 33 N/cm^2 [24]. When using MRI to measure the physiological cross-sectional area and moment arms of the quadriceps muscle, Narici et al estimated that the average force per unit area leveled at 42.9 N/cm^2 [26]. Upon calculating the forces acting along the fibres of each head separately, Narici et al later found that the average force per unit area was 23.7 N/cm^2 for the vastus lateralis and 29.7 N/cm^2 for the vastus medialis [27]. All these above results rely on the availability of accurate methodologies to estimate muscle anthropometry. For example, wherever the muscle's maximal force per unit area is to be non-invasively evaluated, accurate assessments of the cross-sectional area and of the muscle moment arms are essential. Additionally, an accurate measurement of the joint angle as compared with the optimal length of the muscle fibres is needed [25, 28, 29]. MRI images made on the lower extremity provide these data for able-bodied subjects [26, 27]. Thus, the present study provides an extension in the case of SCI.

During the training period follow-up in this study (eight weeks), the maximal isometric torque output of the quadriceps increased by almost 70%. However, morphological studies, incorporating MRI of the quadriceps, have confirmed an overall increase of only 13.5% in the physiological cross-sectional area of this muscle over the same training period. This fact may indicate that conditioning of the trained muscle consists also of a general increase in the intrinsic strength of muscle per unit area. Interestingly, only minor variations in the average force capacity per unit area were observed during the first four weeks of the training where changes primarily consisted of a general increase in the physiological cross-sectional area of the muscle (12%). As training proceeded, the muscle average force per unit area changed from 28 N/cm^2 at the end of the fourth week to 40 N/cm^2 at the end of the eighth week. Similarly, strength training performed on able-bodied subjects has demonstrated that when an increase in muscle size occurs, the changes are less prominent than the increase in voluntary strength of the muscle [13, 30–32]. Ikai and Fukunaga have demonstrated that an increase in voluntary strength per cross-sectional area was observed both in the trained limb, as well as in the contralateral untrained limb [32]. Moreover, Dons and his colleagues have demonstrated that the increase in voluntary strength per cross-sectional area was specific to the training (ie, was pronounced during training, but showed no significant change otherwise) [33]. These findings suggest that strengthening may be caused by a neural adaptation rather then by changes in the intrinsic muscle properties [30 ,34, 35]. In trained muscles, neural adaptation can be attributed to either, or to a combination, of the following processes: increased synchronization of motor unit firing; refitting motor unit recruitment threshold by reversing synaptic efficacy —ie, an increase of high recruitment threshold motor units and reduction of low recruitment threshold motor units [35–37]. While increased synchronization of motor unit firing is associated with increases of voluntary control efforts, synaptic efficacy is peripheral in nature and depends on the size and structure of the pre-synaptic terminal as well as the post-synaptic receptors. We, therefore, suggest that in the case where the trained muscles are disconnected from voluntary control—as is the case in FES of paraplegic subjects—neural adaptation should be attributed to an increase in synaptic efficacy of the motor units, and/or preferential enlargement of the nerve axons; thus reduced recruitment threshold of these axons. The latter was found to be significant in muscle fascicles of reinnervated human quadriceps [4]. We, therefore, propose that specific tension of a single muscle fibre is not affected by training, although the average force per unit area increased from 27 N/cm^2 before training to 40 N/cm^2 after eight weeks of training by FES.

Muscle strengthening may depend on the increase in the number of activated myofibrils, fibre area, myofibrillar area, myofibrillar volume density, and upon the ratio of type I (slow oxidative) and type II (fast-fatigable) fibres [4, 31]. Biopsy studies made on able-bodied subjects showed that the myofibril cross-sectional area increased significantly following training, while the myofibrillar density, defined as the number of filaments within an enclosed area, remained unchanged. Increase in fibre size was observed in both type I and type II fibres, however, in the paralysed muscles trained by FES an increase in the size of type II fibres was accompanied by a marked decrease in their relative number [4].

The results presented in this study reveal a major increase of the cross-sectional area at the region of the RF belly over which the stimulation electrodes were placed. Interestingly, the increase in the cross-sectional area of the RF belly over the first four weeks of training (10.5%) was similar to that observed during the second four weeks (11.4%), whereas the increase in RF volume (or PCSA) over the entire training period (8 weeks) was below 10%. One possible explanation for the above disagreement may lie upon the fact that the stimulation intensity used for training was submaximal; therefore, not all the motor units of the RF, as well as those of the vasti heads, were recruited as the current distribution at the vicinity of their motor points was below the excitation threshold. On the other hand, the current distribution around most or all of the motor points at the area of the RF belly was sufficient to evoke muscle contraction.

Although, no attempts were made to confirm the above explanation in the present study, this issue should be addressed as it may result in a more effective arrangement of the FES electrodes. For example, strengthening and hypertrophy of the quadriceps group may increase significantly upon placing additional FES electrodes over the medial and lateral regions of the quadriceps.

Conclusions

The increase in muscle peak torque over the training period was more prominent than that of the cross-sectional area. Based on referenced studies, we suggest that the increase in the ratio of peak force to muscle cross-sectional area is caused by neural adaptation of the axons and neuromuscular junction rather than by an increase in the muscle fibre-specific tension.

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