IMPACT OF RECRUITMENT LEVEL ON LOCAL MUSCLE FATIGUE: A CLINICAL EVALUATION

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ABSTRACT

This study investigates impact of recruitment level with respect to local muscle fatigue during transcutaneous stimulation of paraplegic quadriceps muscle. Muscle force and muscle dynamics are evaluated during prolonged (10 min) series of tetanic isometric contractions, using a two electrode configuration. Various temporal and stimulus amplitude settings are applied to investigate the following hypothesis: When a muscle is sub maximally recruited using surface stimulation, activated and non-activated parts are independent with respect to occurance of fatigue in activated regions and recovering process in non-activated regions. In the activated regions relative loss of force due to fatigue will be independant of recruitment level.

KEY WORDS: muscle fatigue; muscle force; dynamic muscle activation; transcutaneous stimulation.

INTRODUCTION

At the Twente University and the Roessingh Rehabilitation Center one of the research goals in FES is to optimize the possibilities of transcutaneous neuromuscular stimulation in paraplegic ambulation. Major problems in traditional open-loop controlled walking using Functional Electrical Stimulation (FES) are sensitivity of the system for external disturbances, and early local muscle fatigue which is generally attributed to ischaemia in the activated muscle [1,2]. Especially the latter is reported to deteriorate the functional possibilities of FES systems [3]. To improve (dynamic) system response closed-loop control of stimulation is widely reported in literature [4,5]. Differences between desired and actual system response are corrected for by adapting recruitment level or stimulation frequency. This results in muscle force (continuously) being adapted to external load. Compared to continuous supra maximal activation it may therefore reduce or avoid local muscle fatigue as well.

In the present study the impact of force reduction by decrease of recruitment level was investigated with respect to its effects on local muscle fatigue during transcutaneous stimulation. In general muscle fatigue can be characterized by a range transcutaneous stimulation. In general muscle fatigue can be characterized by a range of activation and force related processes in nerve and muscle which may affect both the electrical and mechanical muscle output. In the present study muscle force was considered, being the most relevant parameter with respect to functionality of FES systems.

In literature various processes and parameters are described which, individually or in combination, affect local muscle fatigue [6,7]. This is related to muscle fiber type as well. However, except long lasting disturbances of ion concentrations, for low activation frequencies support of metabolic products and extinction of catabolic products from the muscle fiber are reported to be most crucial. These are determined by local blood supply and diffusion velocities in muscle tissue, where local blood supply is determined by the difference between local blood pressure and local internal muscle pressure resulting from contraction [8,9]. In partially recruited muscle this results in muscle fatigue being related to both total muscle force and spatial distribution of recruitment over the muscle. When spatial distribution of activated muscle fibers is inhomogeneous local muscle fatigue may show differences over the muscle. Inhomogeneity will depend on the current density distribution in muscle or nerve, and is expected to be strongly present during transcutaneous stimulation. Two additional effects must be mentioned. First spatial effects of recruitment are counteracted by the inverse nature of the recruitment as found during artificial neuromuscular stimulation. Secondly vasodilatation may improve muscle blood flow during dynamic muscle contractions [10,11].

In the present study the following hypothesis is investigated: When a muscle is partially recruited using surface stimulation, activated and non-activated parts are independent with respect to occurance of fatigue in activated regions and recovering process in non-activated regions. In the activated regions relative loss of force due to fatigue will be independant of recruitment level. The hypothesis is tested in paraplegic patients under isometric conditions, activating m. quadriceps with two electrodes. Both muscle force and muscle dynamics are evaluated during 10 min. series of tetanic contractions using both continuous and intermittent activation patterns.

METHODS

Experimental setup

During experiments the patient is in the supine position on a bench. The knee joint is in 30 flexion, the trunk is 45 flexed towards the vertical. The hip is fixed using a belt. The left leg quadriceps is stimulated isometrically using a surface cathode and anode (self adhesive, 4x7 cm) placed over the rectus femoris motor point and near the patella. To measure knee extensor force the tibia is fixed to a force transducer which is placed at 30 cm from the distal edge of the patella, using Velcro straps. The force transducer consists of a half- bridge configuration of two strain gauges on a rigid steel bar connected to a bridge amplifier.

To control stimulation and measure muscle force output we used an IBM-AT computer with AD-facilities (Analog Devices, 12-bit) and a high output impedance current stimulator (mono phasic, rectangular pulses). The pulse parameters could be controlled by the computer. Pulse duration was fixed at 300 us, pulse-rate was fixed at the minimum frequency for a fused contraction: 20 Hz. Pulse amplitude was used as control parameter. During the experiments stimulus amplitude and force are recorded and stored at disk for off-line evaluation. Force was recorded using a sample frequency of 100 Hz to fulfil the Nyquist sample theorem.

Subjects

Experiments are carried out on 5 complete T4-T6 level spinal cord injured patients. The patients have normal excitability of quadriceps muscles and are well trained during at least a 6 month FES exercise program. This program consists of weight lifting twice a day (30 min, ankle load up to 5 kg) and low-load exercise cycling twice a week (30 to 60 min).

Protocol

For each subject a series of 9 fatigue experiments is carried out. Each experiment lasts 10 min. and is followed by 45 min. of rest. During rest, the patient is seated in his wheelchair and is asked to be moderately physically active. Stimulation electrodes are not removed between experiments.

Two stimulation strategies are used, being continuous activation at constant amplitude level and intermittent activation, stimulating at two levels alternately (figure 1). Continuous stimulation is at amplitude levels to obtain 100%, 30%, 10% and 5% of the individually determined maximum quadriceps force (MF). Intermittent stimulation is at amplitude levels to obtain 100% and 30% of MF alternately. One experiment is at alternate levels of 100% and 0% MF. Values of T_H are 0.2 and 0.5 s, and for T_L 0.4 and 1.0 s. This is based on values found in a previous study concerning on-off controlled stabilization of paraplegic knee joint [12].

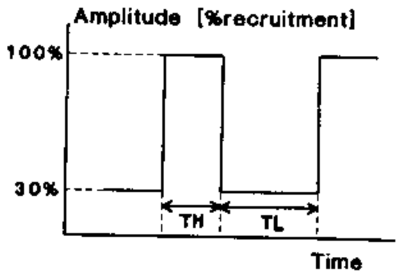

Figure 1. Activation pattern used during intermittent stimulation. Amplitude levels correspond to 30% and 100% recruitment (duration T_L, T_H resp.). Note that 30% of the muscle is continuously activated.

Prior to each fatigue experiment identification experiments are done. Dynamics of the passive leg-transducer system, dynamics of active muscle-leg system and stimulus amplitude to force relation (i.e. recruitment curve) are determined. To determine the dynamics of the passive leg-transducer system, response to a step input is determined. The dynamics of the active muscle-leg system is identified using a 10 s pseudo random binary sequence of alternate stimulation at the amplitude levels used in the fatigue tests. To determine the stimulus amplitude to force relation, slow ramp-up and ramp-down of stimulus amplitude is used (0 to 100 mA; 10s up, 10s down). This is used as a reference for the required amplitude levels in the fatigue test. After the identification experiments 5 min. of rest are taken, the patient remaining in supine position on the bench.

RESULTS

Continuous muscle activation

Figure 2 shows a typical example of the force measured at the tibia for various levels of recruitment. It can be seen how after an initial increase of force, muscle force decreases rapidly in time for all levels of recruitment. Force reaches a steady-state level within 60 to 70 s after start of stimulation.

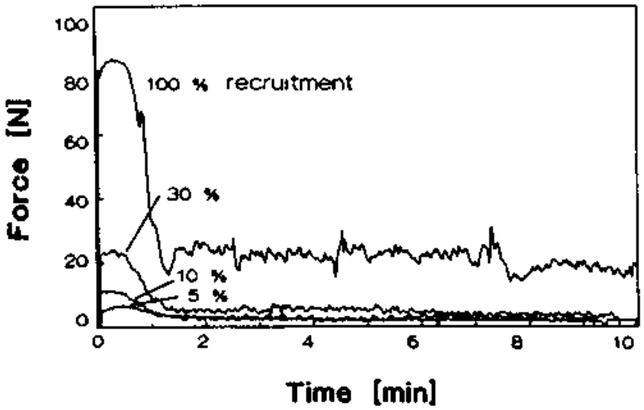

Figure 2. Typical example of force decrease during continuous activation of quadriceps at various levels of recruitment. Significant force decrease is found even at 5% recruitment.

Steady-state level is nearly linear proportional to recruitment level: force decreases to 22% of the initial force for 100% recruitment, to 24% initial for 30% recruitment, to 23% initial for 10% and to 28% initial force for 5% recruitment. This confirms the hypothesis of recruitment being highly spatially oriented and high local muscle pressure i(nducing local occlusion and fatiguing the activated muscle fraction) even at low levels of recruitment. At various levels of recruitment muscle force decrease stabilizes at levels which induce comparable absolute force levels per recruited muscle fraction.

Irregularities in force output can be seen after steady-state is reached. This indicates fatigue and recovering processes to be non- continuous, and to occur synchronously in larger muscle fractions.

Intermittent stimulation

Figure 3 shows the force response of the quadriceps (measured at the tibia) when activated intermittent according to the pattern of fig.1. Shown are typical results for T_H= 0.5 s, T_L= 0.4 s (fig 3a) and T_H= 0.2 s, T_L= 1.0 s (fig 3b), where F_{min} corresponds to 30% recruitment (continuously activated muscle partition), F_{max} to 100% recruitment and F_{max}-F_{min} to the response of the on-off activated muscle partition. It can be seen that the minimum force level (30% recruitment) tends to decrease similar to what was found in fig.2. Force output of the intermittent activated muscle partition shows a decrease which depends on T_H and T_L. Steady-state level ranges from about 50% (fig 3a) to 100% (fig 3b) of the initial value. When considering also the effective duty-cycle of the muscle (which is less then 1 during intermittent stimulation) this means that the time-averaged force output at steady- state ranges from 28% (fig 3a) to 10% (fig 3b) initial. This means that the **time-average** force output is comparable to what is found during continuous muscle activation or less, while **dynamic range** of force output after steady-state is reached increases from 30% during continuous maximal activation to 50-100% during intermittent activation.

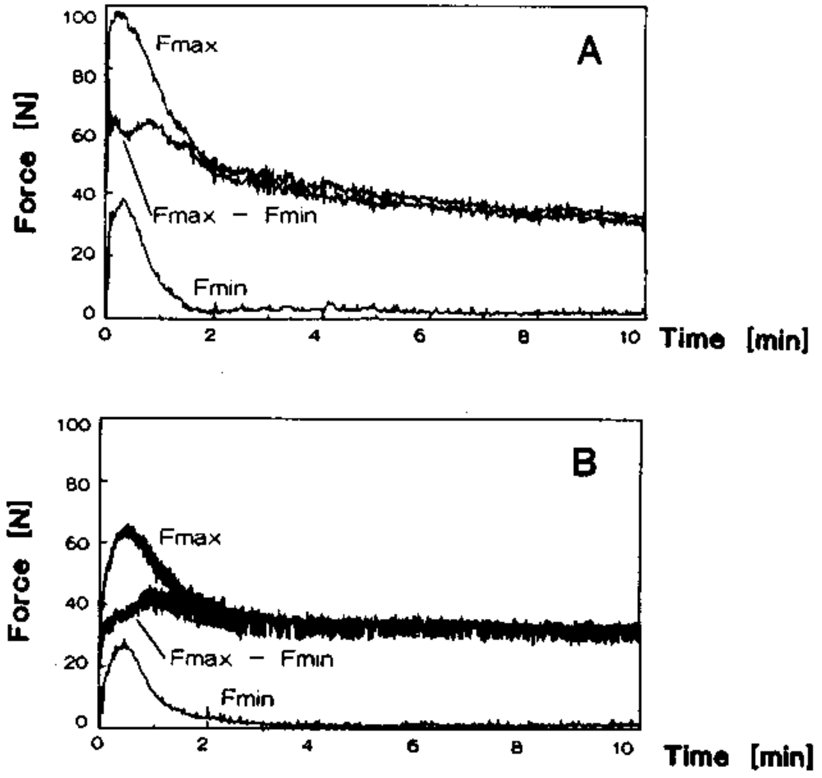

Figure 3. Force response during intermittent activation of quadriceps according the stimulation pattern of fig. 1. F_{min} corresponds to 30% recruitment (continuously activated), F_{max} to 100% recruitment and F_{max}-F_{min} to the response of the on-off activated muscle partition.
a: T_H(=100% recr.) = 0.5 s, T_L(=30% recr.) = 0.4 s.
b: T_H(=100% recr.) = 0.2 s, T_L(=30% recr.) = 1.0 s.

Compared to fig 2 the relative initial force increase in the continuously activated muscle partition (Fmin) is high. This may be caused by recruitment not being stable at 30% but increasing, or to the intermittently activated muscle partition affecting e.g. blood flow in the continuously activated muscle partition.

DISCUSSION

The first results obtained in this study confirm the hypothesis of recruitment being highly **spatially oriented** during transcutaneous activation of quadriceps muscle: During **continuous** isometric contractions muscle force was shown to decrease to a steady-state level which is nearly linear proportional to the level of recruitment. Force decrease is clearly present, even at 5% recruitment level. This is consistent with the idea of local occlusion to induce force reduction, while at various levels of recruitment muscle force decrease stabilizes at levels which induce comparable absolute force levels per recruited muscle fraction. Consequently our results indicate that e.g. long stand-times obtained with supra maximal stimulation of quadriceps (in literature stand-times of 'several' hours are reported) can only be obtained under very low external load conditions (caused by e.g. specific posture or the use of mechanical stabilization). Also, during continuous muscle activation at **sub-maximal** levels constant force output requires continuous increase of recruitment level.

During **intermittent** activation of quadriceps the lower force level (30% recruitment) was found to decrease comparable to during continuous activation. The force output of intermittently activated muscle fibers decreases depending on temporal parameters of activation pattern. For low duty-cycle force even stabilizes at its initial level. The dynamic range of force output after steady-state is reached increases compared to during continuous maximal activation for all duty cycles tested.

It is concluded that during transcutaneous activation of quadriceps muscle intermittent activation may be favorable to continuous activation, even for short contraction/relaxation times. Although for high duty-cycles positive effects are limited this may have implications with respect to the design of closed-loop systems for the regulation of muscle force.

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