Fatigue of intermittently stimulated quadriceps during imposed cyclical lower leg movements

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Introduction

A major issue in the control of functional electrical stimulation (FES) of paralysed muscles is the decay of muscle force as a result of fatigue under sustained (continuous and intermittent) stimulation (Andrews et al 1989, Boom et al 1992, Levy et al 1990, Mulder et al submitted). Stimulated paralyzed human quadriceps fatigue under isometric condition can be described by an exponential decay (Boom et al 1992, Levy et al 1990, Mulder et al submitted). In this study the torque of intermittently stimulated paralysed human knee extensors during (isokinetic) cyclical lower leg movements has been investigated.

Methods

A protocol was designed to compare overall loss of tetanic torque at the knee joint during sustained intermittent stimulation at different isokinetic velocities. The angle and velocity ranges were limited by the anatomical restrictions of the lower leg, the restrictions imposed by the experimental set-up (a KINCOM 125ES (Kinetic Communicator Exercise System) dynamometer bench) and the desire to maintain a constant cycle time, comparable to a walking cycle. The experimental set-up is shown in figure 1. The influence of duty cycle and stimulation frequency, at isokinetic joint movement, was also investigated. Identification trials, determining the torque-angle (isometric) and torque-angular velocity (isokinetic, measured at 40 deg. of knee flexion) relations, were performed. Pulsewidth and amplitude were set to obtain maximal recruitment. The interpulse intervals (IPI) used were 20 and 40 msec, both ensuring a fused contraction. Force, angular position, and velocity were sampled at 100 Hz. These signals and stimulus data were stored on disk for off-line analysis.

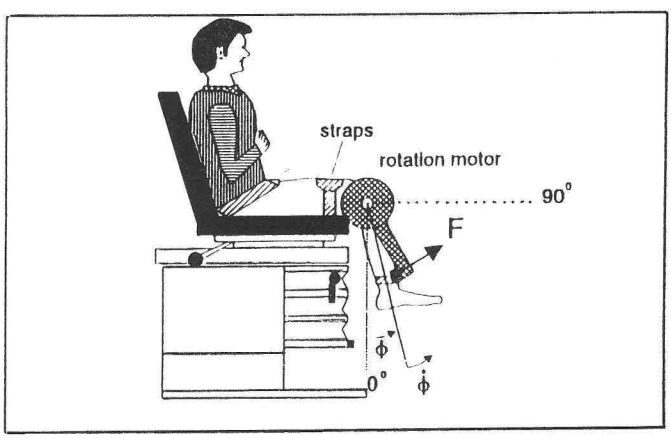

Figure 1. Schematic of experimental set-up. The angular position and velocity, measured at the motor axis, are defined positive in extension motion with zero as indicated. The patient is strapped at the hip and above the knee to measure knee torque (at the tibia) only and to ensure static position of the body.

The subjects who participated in this study were complete T5-T6 level spinal cord injured patients. All had normal excitable quadriceps muscle and had been enrolled in the FES training program of the rehabilitation center *'t Roessingh* (Enschede, The Netherlands).

Results

From the resulting torque, obtained by subtracting the averaged passive torque from the measured torque at the knee, the maximum and torque-time integral (TTI) per swing were calculated. The TTI was obtained by summating over a constant time period of the swing where the contraction takes place, including activation and relaxation phases, with constant velocity. The typical exponential decay of isometric quadriceps torque, reaching asymptotic values (Boom et al 1992, Levy et al 1990, Mulder et al submitted), resembles the overall loss of tetanic torque and TTI during sustained intermittent stimulation at isokinetic condition as found in this study. Additionally, the results indicate a significant dependence of the rate and magnitude of decay on the contraction velocity, which has not been reported before. Higher velocities result in a larger and faster decay of maximal torque and TTI. Also, the rate and magnitude of fatigue for concentric contractions appears to be directly related to duty cycle and 1/IPI.

Electrically stimulated muscle is a nonlinear dynamic system, exhibiting nonlinear dependence on position and velocity, which make it extremely difficult to control. Our identification results resemble the output of muscle model structures reported in animal experiments. The typical Gaussian-type dependence of the generated torque on the angle was also found. Hill's equation, favoured by many researchers for curve-fitting the torque-velocity relation for concentric contractions, is also representative for our results.

Discussion

The dependence of the fatigue curve of transcutaneously stimulated human quadriceps on the isokinetic knee joint velocity and the applied stimulation parameters (duty cycle, IPI) is an important factor in the design of optimal control systems for FES which pursue minimization of muscle fatigue. Basically, the results given above indicate that within the (lower) boundary conditions for a given task (ontime/IPI), which is equal to the number of pulses given, should be minimized to postpone fatigue. The results may contribute to the derivation of an optimization criterion, describing muscle fatigue as a function of both joint movement and stimulation parameters.

References

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