DETERMINATION OF EFFICIENT STIMULATION PATTERNS FOR FES - CYCLING

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Abstract: To determine efficient stimulation patterns for FES-cycling an instrumented tricycle for persons with spinal cord injury was developed. With the help of an integrated force measurement system in the cranks and various automated, PC controlled measurement routines, the relation between the stimulation parameters and the power output of the stimulated muscles can be analysed. Beside its test function the tricycle can also be used as a training device for regular FES-cycling.

Introduction

Functional electrical stimulation (FES) of the lower limbs enables persons with a spinal cord injury to perform cycling on adapted tricycles [1], [2]. FES-cycling is used as a supporting therapy and has numerous positive physiological and psychological effects [3], [4]. Through the activation of additional muscle mass the condition of the cardiovascular and the pulmonary system is improved [5]. Further benefits of FES training are the reduction of muscle atrophy and the increase of bone density [6].

It was the aim of this project to develop a test tricycle which allows an easy determination of efficient stimulation patterns for the individual cyclist and to gather information on the relation between stimulation parameters and muscle contraction. By automated test routines the test duration can be kept as short as possible.

Materials

A commercially available tricycle was adapted to meet the special requirements of this study (see Fig. 1). In the modified cranks a force measurement system based on strain gauge technology and an optical angle encoder are integrated.

The cycle can be used as a stationary or mobile device. During the stationary measurements the rear wheel is lifted off the ground. A motor integrated in the hub of the rear wheel can move the cranks with constant angular velocity or fix them on a chosen angular position. When the tricycle is used for mobile FES-cycling the motor can support the cyclist in case of gradients or muscle fatigue.

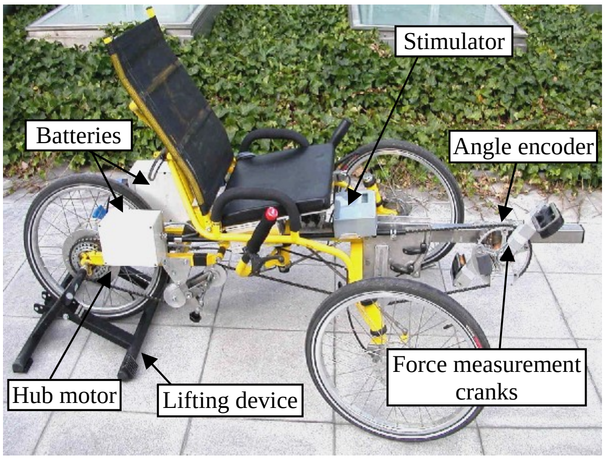

Figure 1: Side view of the tricycle with its components.

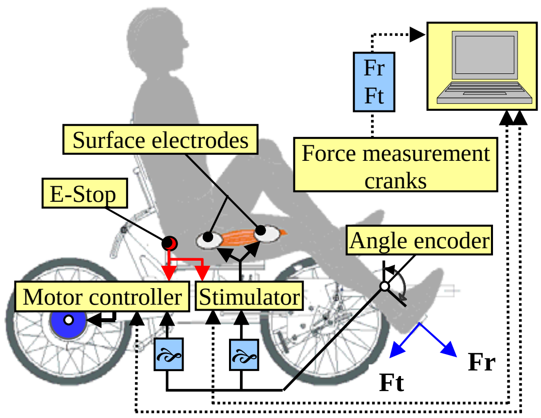

Figure 2: Schema of the test tricycle and control components. symbolises the crank angle which is given by the angle encoder and processed by the stimulator and the motor controller. Fr and Ft stand for the radial and tangential forces which the legs transfer onto the pedals, respectively. From the Ft the applied drive torque and power can be deduced.

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The communication paths between the control components are shown in Fig. 2. The dotted lines stand for serial communication, the solid lines for hardware connections in the system. The 10-channel current controlled stimulator activates the involved muscles via surface electrodes in defined crank angle intervals or over given time periods. By pushing the emergency stop the stimulation is interrupted and the motor is switched into idle mode. The coordination tasks are carried out by a PC which is controlling, pre-defined isometric and isokinetic measurement routines and is processing the data from the force measurement cranks. One complete data block (force values, crank angle, stimulation settings and motor status) is received every 5 ms.

Ortheses (Fig. 3) are mounted on the pedals to stabilise the legs in the sagittal plane and prevent the feet from gliding off the pedals.

Figure 3: Ortheses

Methods

Five male paraplegics with complete lesions between Th3 and Th11 who are performing regular FES training (about 4 hours per week) volunteered for a series of measurements on the tricycle. The study was approved by the ethical commission from Lucerne, Switzerland and all test subjects gave their written informed consent. Three test routines were carried out:

- *Detailed static measurements*: The crank is fixed by the motor at a defined angular position (e.g. 30° for the right leg, 0° is where the right crank points vertically up). The muscle, here m. quadriceps, is stimulated with increasing intensity from 0 to 120 mA in steps of 10 mA, frequency from 0 to 100 Hz in steps of 10Hz and pulse duration from 0 to 350 ③s in steps of 50 ③s. Each stimulation burst lasts one second, to guarantee that the measured forces at the end of the stimulation interval are not influenced by muscle activation dynamics. By subtracting the passive forces that are applied on the pedals before stimulation (due to gravity) from the recorded forces at the end of the stimulation interval, the active pedal forces can be calculated. Under the assumption that the electrical field does not lead to co-stimulation of other muscles, the active forces on the pedal are directly caused by the contraction forces of the stimulated muscle. From these results the influence of varying stimulation parameters on the measured forces at the cranks can be determined.

- *"Quasistatic" measurements*: During these measurements the cranks are moved by the motor at a constant angular velocity of 3 rpm. After one passive rotation without stimulation the examined muscles (see Fig.4) are stimulated one by one in an angular range that is larger than their approximated concentric range. By fixing the ankle joints the kinematics of the pedaling movement are pre-defined and consequently the region where the muscle is working concentrically and is producing positive pedalling power can be determined for each muscle separately. The m. quadriceps femoris is stimulated from 250° to 140°, the m. gluteus maximus from 270° to 180°, and the hamstrings are activated in the angular range from 280° to 230°. The exact range in which each stimulated muscle generates positive active drive torque can be analyzed after subtracting the passive from the active tangential forces (Fts).

- *"Step" measurements*: A step mode routine is run where the crank is fixed in 15° steps over the whole crank rotation and at each position one stimulation burst of a duration of 1 s is applied to the examined muscle. Processing the data of the Ft gives - similar to the "quasistatic" result - the crank angle range where the muscle can produce positive active drive torque. This allows us to compare the two test routines and to validate the "quasistatic" measurements.

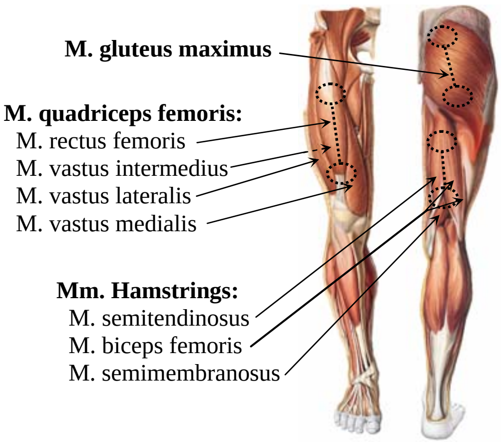

Figure 4: Stimulated muscle groups shown on the right leg. The position of the three pairs of surface electrodes is indicated by the dotted ellipses. Picture from [7].

In Fig. 4 the examined muscle groups and the stimulation areas are shown.

Due to the pre-programmed automated measurement routines the complete measuring procedure as described took only about one hour for each patient.

Results

Results from the detailed static measurements

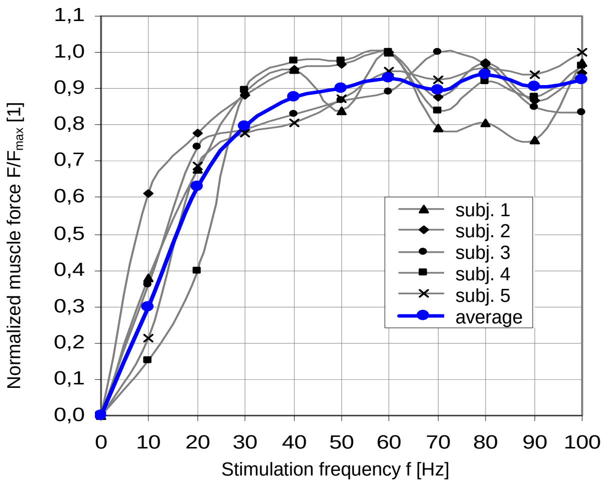

Figure 5: Relation between stimulation frequency and normalized muscle force. (Stimulation amplitude I=100mA, pulse duration D=300 ③s).

In Fig. 5 the relation between stimulation frequency and normalized muscle force is shown. Each curve has been normalized by its maximum value. From the results can be deduced that above a frequency of about 40 Hz the contraction force is not considerably increased. Considering the fact that muscles fatigue sooner at higher stimulation frequencies [8] a stimulation frequency between 40 and 50 Hz for FES-cycling seems to be a good choice.

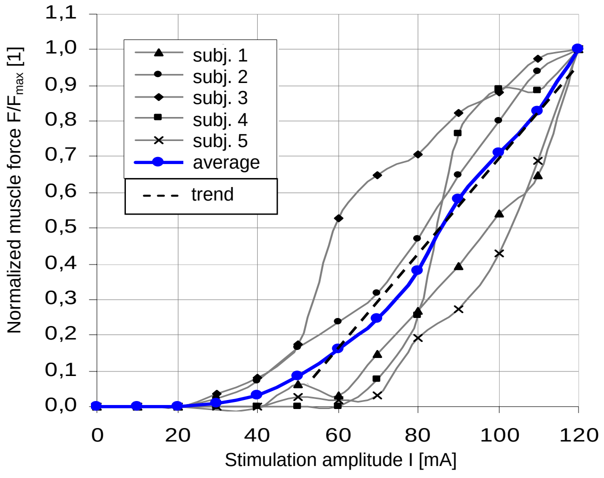

Figure 6: Relation between stimulation amplitude and normalized muscle force. (Stimulation frequency f=50 Hz, pulse duration D=300 ③s)

The results of the static measurements with varying stimulation amplitude are shown in Fig. 6. The threshold value of the stimulation amplitude lies in the range from 20 to 60 mA. For stimulation amplitudes above about 50 mA or 10 % of active force output the averaged force value follows a linear tendency as symbolized by the dotted line.

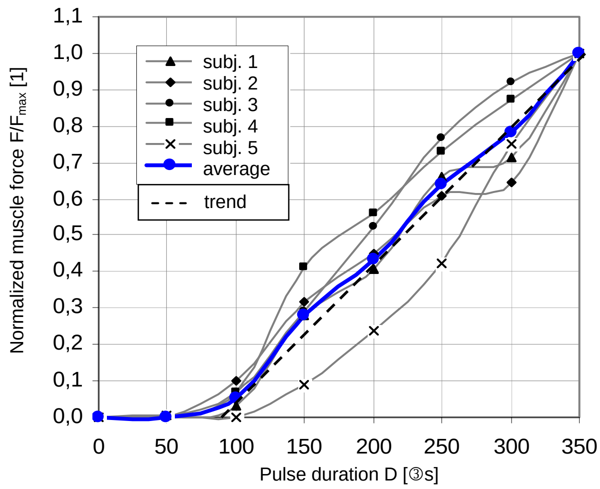

Figure 7: Relation between pulse duration and normalized muscle force. (Stimulation frequency f=50 Hz, stimulation amplitude 100 mA)

The relation between the pulse duration and the force output of the muscle is shown in Fig. 7. Above a pulse duration of 100 ③s the strengths of the muscle contraction increases when stimulating with higher pulse duration. This relation can again be approximated linearly.

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Results from the "quasistatic" and "step" measurements

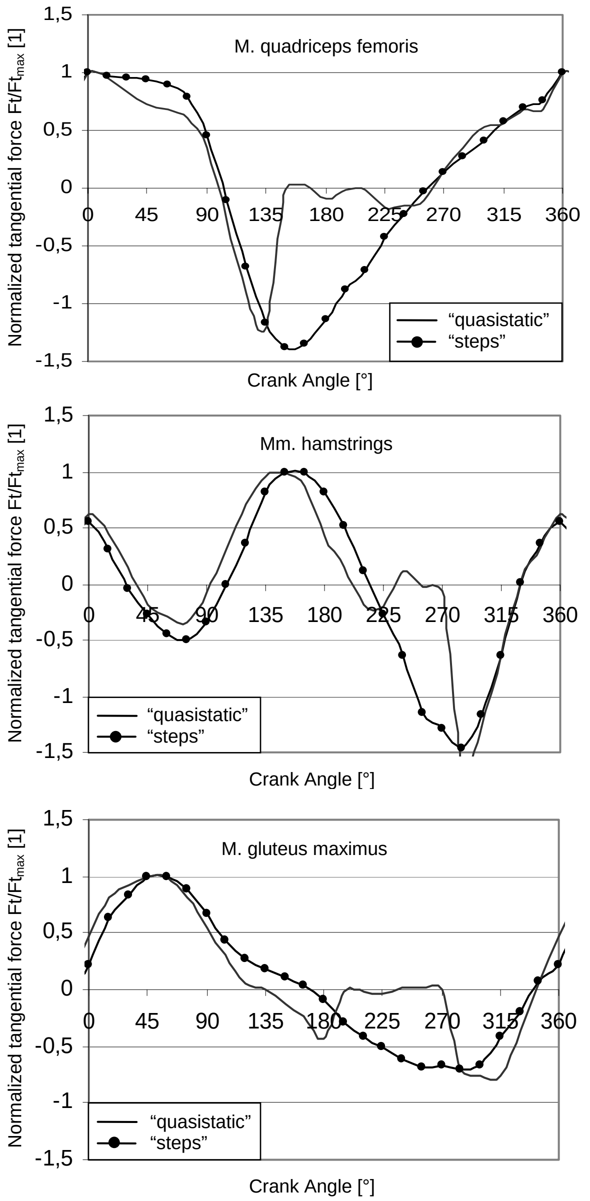


Figure 8: Averaged and normalized active Fts of the examined muscles from the "quasistatic" and the "step" measurements. The passive forces have been subtracted.

Fig. 8 shows the averaged and normalized active pedal Fts. From the "step" measurements active force values at each 15° step around the complete rotation of the crank can be determined. During the "quasistatic" measurements the muscles are not stimulated during most of the approximated eccentric range, consequently the active forces are around zero in this range. It is interesting, that the results for the mm. hamstrings show two angular regions with positive Fts.

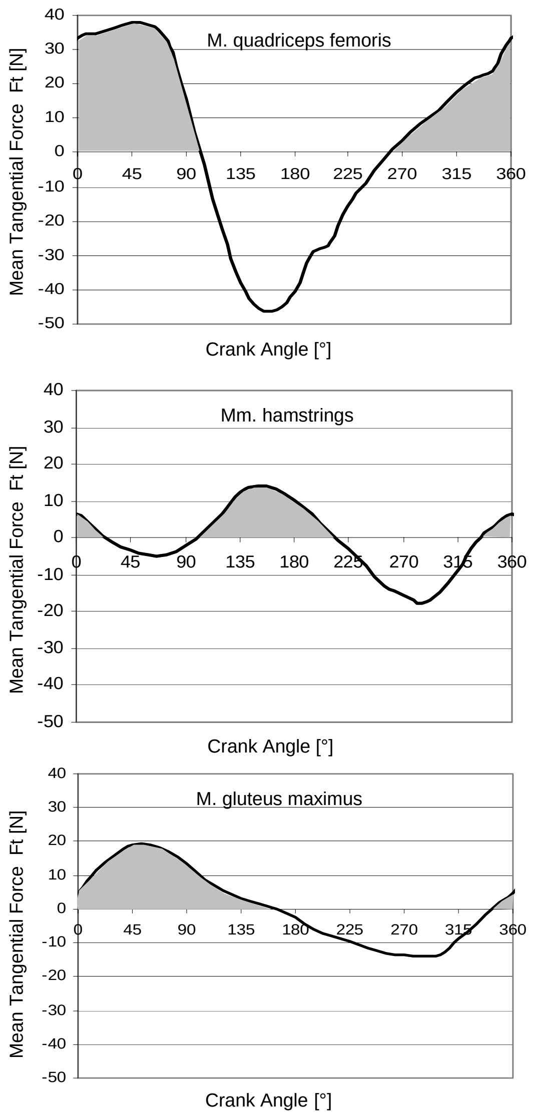
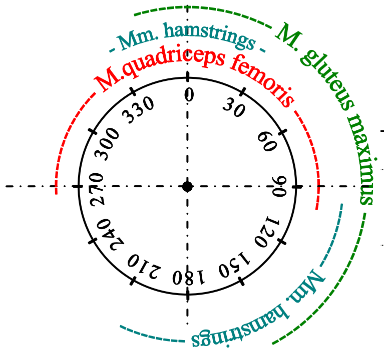


Figure 9: Comparison of the averaged (5 subjects) active Fts of the involved muscle groups. The grey accentuated surfaces indicate the angular regions where the muscles produce a positive Ft. For constant crank angular velocity the surface areas are directly proportional to the average active drive power applied during one rotation. (φ = 0° when right crank is in upper vertical position)

In Fig. 9 the averaged Ft values of the "step" measurements are depicted and the areas of positive values are accentuated by the grey coloured regions. By comparing the surface areas the proportional contribution of the specific to the total power output when all three muscle groups are stimulated in their concentric ranges during pedalling can be estimated. Averaged over the 5 tested subjects the m. quadriceps femoris contributes about 58%, the mm. hamstrings 18% and the m. gluteus maximus about 24% of the total averaged active power over a full rotation of the crank.



Muscle	Stimulation range [°]
M.quad.	263 - 101
Mm. ham.	330 - 32
	97 - 210
M. glut.	342-150

Figure 10: Averaged stimulation ranges from the muscles of the right leg

In Fig. 10 the regions of the crank cycle where the muscles generate positive torque are summarized. These settings can be used as basic parameters for the stimulator when no individual parameter determination is available. It has to be considered that these are results from (quasi)static measurements and muscle activation and deactivation times have not been taken into account.

Discussion

As muscle condition is very different among patients due to factors like training status, spasms and time since injury, it is important to test the relation between stimulation parameters and generated muscle forces for each patient individually. Based on the results of the detailed static measurements it can be predicted, which stimulation parameters are suitable for cycling training of the individual patient, and which consequences parameter changes may have. Here only the quadriceps muscle was tested in the detailed static measurements. To get information on the condition and behaviour of other muscles of the patient, the test routine has to be repeated with this muscle. Muscle fatigue is another issue which is not directly included in the measurement routines. According to [8] muscle fatigue can be kept low by choosing stimulation frequencies below 50 Hz.

The "quasistatic" measurements show similar results like the static "step" measurements. Both of them may be used to determine the crank angle areas where the stimulated muscles induce positive active Fts and consequently positive active driving power. The reason for the two regions where the mm. hamstrings generate positive driving power may be the biarticularity of the muscle group. At each point of the movement the relation of the moment arms at hip and knee can affect the function of the muscle as hip extensor and knee flexor.

In FES cycling with locked ankle joint the kinematics of the movement are pre-defined, and only the pedal forces are influenced by the generated muscle forces. Consequently, investigations on single muscles can give information on the generated muscle forces and torques when more muscles are stimulated during one rotation in the practical application of FES cycling.

For higher angular velocities of the crank, muscle activation and deactivation times have to be considered by shifting begin and end of the stimulation intervals accordingly. Investigations on these parameters have been done before [9].

The prediction of the relative active power output of the single stimulated muscles is only valid if the subject's muscles have the same relative strength as the average of the measured subjects. Additionally, the daily condition of the patient and his spasticity may considerably influence the relative strength of the single muscle groups and have an impact on the power output but not on the optimal stimulation pattern.

Conclusion

With the predefined test routines and the short test duration the instrumented tricycle offers an efficient tool to determine individual muscle parameters and stimulation patterns for FES-cycling.

Acknowledgement

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