A Comparison of Functional Electrical and Magnetic Stimulation for Propelled Cycling of Paretic Patients

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Objective: To compare isometric torque and cycling power, smoothness and symmetry using repetitive functional magnetic stimulation (FMS) and functional electrical stimulation (FES) in patients with paretic legs with preserved sensibility and in patients without sensibility.

Design: Repeated-measures design.

Setting: Laboratory setting.

Participants: Eleven subjects with complete spinal cord injury (SCI) and 29 subjects with chronic hemiparesis (16.6 ± 5.5mo poststroke) volunteered.

Interventions: Using a tricycle testbed, participants were exposed to isometric measurements and ergometric cycling experiments, performed during both 20Hz FMS and FES stimulation. Subjects with hemiparesis and with complete SCI were stimulated at maximally tolerable level and maximal intensity, respectively.

Main Outcome Measures: Maximal isometric pedaling torque and mean ergometric power, smoothness, and symmetry were recorded for voluntary, FES, and FMS conditions.

Results: Two different patterns of the efficacy of FMS were identified. (1) Patients with complete SCI did not benefit (less torque and power was evoked with FMS than with FES, P < .003 and 10^-4 respectively). (2) Patients with hemiplegia and preserved sensibility could improve their torque output (P < .05), smoothness, and symmetry of pedaling (P < .05 ) with FMS more than with FES.

Conclusions: FMS is a potential alternative to surface FES of the large thigh musculature in stimulation-supported cycling of patients with partially or completely preserved sensibility.

Key Words: Magnetic stimulation therapy; Pain; Power; Rehabilitation; Spinal cord injuries; Stroke; Torque.

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FUNCTIONAL ELECTRICAL stimulation is a promising rehabilitation technique for artificially activating muscles that are not under voluntary control after an SCI or a cerebrovascular insult. Possible applications of FES are to propel or support mobility (gait or cycling) and to make possible conditioning exercises. The advantage of cycling is that it can be maintained for reasonably long periods and the risk of fall is low.

FES-propelled cycling in persons with complete SCI is known to train the cardiovascular system, to strengthen the muscles, and to improve cycling mobility. Most of the literature on FES cycling focuses on patients with complete SCI, although the stroke population is approximately 10-fold that of the SCI population. It is thought that electrical stimulation can also be used in the latter case for training purposes as well as for achieving ultimate functional improvement.

However, FES can be clinically impractical in the stroke population, because it induces pain as a result of unavoidable stimulation of the skin receptors, including Aδ myelinated heat nociceptors and C-fiber nociceptors. This reason, 8 of 46 subjects in a study on the efficacy of FES in patients with acute stroke could not tolerate FES treatment. In the study by Yan et al., thigh stimulation intensities of 20 to 30mA were used to achieve weight-supported knee joint movement. In 2 studies on leg stimulation—supported gait in the same group, the stimulation intensity was set to 50 to 85mA in an effort to achieve limb movement at the subject’s comfort threshold. However, only small or submaximal isometric torques could be generated at those intensities, as seen in the torque recruitment curve of the quadriceps. It has been shown that increases in quadriceps femoris strength in a healthy population who trained with FES correlated with training contraction intensity and duration. It was concluded that the relative increase in isometric strength resulting from training with FES might be determined by the ability of the subjects to tolerate longer and more forceful contractions. Our previous study also demonstrated that cycling power and smoothness in patients with acute stroke are limited by the patient’s ability to tolerate stimulation current.

In contrast, by using time-varying electromagnetic fields to induce eddy currents in the adjacent volume without passing the skin, repetitive FMS activates the nerve innervating the muscle without stimulating the skin nociceptors. Moreover, magnetic stimulation does not produce radial current, which activates pain nerves in the skin best.

However, compared with electrical stimulators, magnetic stimulators are bulkier, and they cannot provide focal stimulation. Nonetheless, stationary cycling with FMS stimulates the large muscles of the thigh and is considered an adequate application of magnetic stimulation. Human movement, partic-
ularly cycling, is equally dependent on isometric force and power output.²² To our knowledge, the reports on magnetic stimulation to generate muscle force in legs of healthy persons are rare,²³,²⁴ and there are no reports at all on the generation of power in persons with only partially preserved or lost sensibility. Because it is painless compared with electrical stimulation, magnetic stimulation is used as a nonvolitional assessment technique of quadriceps muscle strength²⁶ and endurance.²⁶

The goal of the present study was to compare stimulation-induced isometric forces, power, smoothness of movement, and symmetry of pedal forces during cycling using electrical and magnetic stimulation in paretic persons with preserved residual sensibility (stroke group) or with complete loss of sensibility (SCI group). We were also interested in determining whether electrical stimulation and magnetic stimulation induce contraction in different parts of the muscle (superficial vs deep).

METHODS

Subjects

Stroke group. Twenty-nine subjects (14 women, 15 men; age, 65.1 ± 10.1 y) with chronic poststroke hemiparesis (16.6 ± 5.5 mo poststroke) in a stable condition took part in the study. Mobility ranged from impaired to wheelchair confinement (Functional Ambulation Category 1.86 ± 1.1). Most of these subjects were not able to stand independently and were therefore considered unsuitable candidates for treadmill therapy.²⁷

SCI group. Eleven otherwise healthy subjects (3 women, 8 men; age, 46.8 ± 12.1 y) with chronic (10.9 ± 8.1 y since injury) complete SCI (ASIA-A) and low levels of muscle spasm (MAS 1.0 ± 0.7). Moderately increased muscle tone during knee extension was obvious in all hemiparetic subjects (MAS 1.0 ± 0.7).

SCI group. Stroke group.

Study Design

Each subject underwent 3 different experimental sessions: (1) isometric measurements using FES and FMS, (2) ergometry using FES, and (3) ergometry using FMS. The session order was randomized, and the 3 types of experiments were performed first in the SCI group and later in the stroke group. Each session was performed on a different day over a period of 6 weeks (SCI group) and 15 weeks (stroke group).

Electrical Stimulation

The quadriceps and hamstrings muscle groups were electrically stimulated during ergometric cycling (in the stroke group only on the affected side). For isometric measurements, only the left quadriceps group was stimulated in the SCI group and only the affected side in the stroke group. Pairs of flexible adhesive gel electrodes (4.5 × 9.5 cm²)²⁵ were placed on the skin over the proximal and distal fourth of each muscle bulk (see similar studies).²⁶,²³,²⁹ A constant-current 8-channel stimulator provided the stimulation current (rectangular, biphasic, charged balanced pulses; frequency, 20 Hz; maximum pulse amplitude, 127 mA; constant pulse width, 300 µs).

Magnetic Stimulation

Two repetitive magnetic stimulators were used. The Magstim Rapid stimulator provided double cosine pulses (2 cosine half-periods, each with 125 µs pulse width) and with a 2-tesla maximal magnetic induction. The P-Stim 160 magnetic stimulator generated double cosine pulses (each with 160 µs pulse width) and with a 1-tesla maximal magnetic induction. The frequency was 20 Hz, the same as in electrical stimulation. Two round magnetic coils (diameter, 90 mm; 23.3 µH inductance) were placed on the subject’s clothes overlying the quadriceps muscle and were tilted 45° to the frontal plane. They were fastened to the proximal half of the muscle bulk by straps made of foam and Velcro (fig 1).

The stimulation burst durations (see below) were chosen according to the maximally tolerable coil heating.

During the isometric measurements and ergometric cycling, the electrical and the magnetic stimulators were controlled from a personal computer by serial communication. The muscle stimulator was directed to induce muscle contractions on both sides in the SCI group in order to propel cycling and on the affected side in the stroke group to support volitional pedaling. Muscle contractions were induced at the appropriate crank angles.⁴

Isometric Measurements

A stationary tricycle with its front wheel replaced by a torque transducer served as the test bed for isometric torque measurements (see fig 1). An 11-bit incremental encoder, synchronized to turn with the crankshaft, determined the actual position of the crank. Angular and force data were read in by the personal computer at a sample rate of 20 Hz. The ankle joint was immobilized at 90°, and leg movement was restricted to the sagittal plane using shank and foot orthoses. The crank angle was set and held automatically by an alternate current-servomotor position-controlled by a servo-controller. Volitionally or electrically evoked maximal isometric torques of the left leg were measured at a 100° crank angle (see fig 1, inset), with reference to the 0° defined by the left, backward-pointing crank arm (280° for the right leg because of a shift of 180°).

Stroke group. The maximal torque generated by the quadriceps group was considered only on the affected side. After peak volitional torque on this side was recorded, the subject was instructed to relax for 20 to 30 seconds. Then, beginning at the motor threshold, the muscle was stimulated by FES bursts (fig 2) with amplitudes increasing stepwise (5 mA) until the maximally tolerable intensity (indicated by the subject) was reached. Next, while the muscle had been electrically stimulated for 50 seconds at the maximally tolerable FES intensity, FMS bursts that increased stepwise (15%) until the maximally tolerated FMS intensity was reached were applied to the muscle. Finally, the muscle was stimulated twice by the same sequence of FMS bursts as before. The peak torque and corresponding stimulation intensities were recorded in the sequence FES, FMS + FES, and FMS (see fig 2). The burst duration amounted to 1.5 seconds.

SCI group. The maximal torque generated by the quadriceps group was recorded only at the left side. The muscle was successively stimulated by FMS pulses of amplitudes of 40%, 60%, 80%, and 100%, and with a burst duration of 1.5 seconds (fig 3).

Next, while the muscle had been electrically stimulated for 50 seconds at the maximal intensity, the same sequence of FMS bursts as used before was applied to the muscle. Peak torque and corresponding stimulation intensities were recorded in the sequence FMS, FES, and FES + FMS (see fig 3).
**Ergometric Measurements**

Dynamic measurements were performed on the stationary tricycle test bed by controlling the resistance torque (motor-powered brake). The braking torque on the crank measured by the torque transducer ranged from 0.15Nm to 7.30Nm. It was set individually at the maximal magnitude at which the patient could cycle for about 3 minutes at a cadence of 35 to 55 rpm. FES and FMS were applied in a randomized order, each in a separate session.

**Stroke group.** The subjects cycled for 3 minutes. This consisted solely of volitional cycling in alternation with stimulation-supported cycling, each time for periods of 30 seconds. Patients were instructed to try to achieve smooth pedaling. The maximally tolerable stimulation intensity, determined in isometric tests for each subject, was also used in the ergometric tests. Data for the last 15 seconds of the 30-second periods were collected for each subject and each condition (3 FES, 3 FMS, 6 nonstimulated periods).

**SCI group.** Data for 2 minutes of pedaling propelled by stimulation were recorded. The stimulation intensity was gradually increased over about 10 to 30 seconds to the maximum intensity (FES, 127mA; and FMS, 100%) while maintaining the cadence in the range of 35 to 55 rpm.

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**Fig 1.** Isometric and cycling measurement setup. Both FMS and FES stimulation are possible. A subject with complete SCI performing FMS-propelled cycling using 2 magnetic stimulators can be seen. (1) torque transducer, (2) angular encoder, (3) right side repetitive magnetic stimulator, (4) left side coil, (4, 5) straps made of foam and Velcro. Inset: definition of the crank angle.

**Fig 2.** Isometric measurements performed on a representative subject belonging to the stroke group. Starting from the motor threshold, stepwise-increasing FES and FMS burst amplitudes were applied until maximum tolerable intensity was reached in the first and the last part of the protocol, respectively. Combined stimulation (the FMS burst sequence was superimposed on the FES) was applied in the middle part of the protocol.

**Fig 3.** Isometric measurements performed on a representative subject belonging to the SCI group. In the first part of the test, starting from the motor threshold, stepwise-increasing FMS burst amplitudes were used until maximal intensity was reached. In the second part of the test, combined stimulation was applied (the FMS burst sequence was superimposed twice on the FES).
**Data Processing**

Crank angular position and torque were recorded; cadence and power were calculated (also cycling smoothness and symmetry in the stroke group). Cadence was computed from the change in crank position over time. This was digitally filtered with a second-order Butterworth filter with a cutoff frequency of 4Hz by using Matlab v. 6.1.0.1 Power was defined as the product of cadence and torque. To measure the smoothness of reciprocal pedaling, a method proposed in the literature was used. The smoothness, defined as the summation of the curvature for each instantaneous cranking speed, is given as

\[ RI = \sum_{n} dR/ds \]

where \( R \) is the instantaneous cranking speed after tenth-order polynomial curve fitting and \( s \) is the crank position. In smooth pedaling, the smoothness will approach 0. The definition of the smoothness is illustrated by the upper graph of fig 4.

To measure symmetry, the maximum of the circular autocorrelation coefficient of the crank torque profile (see fig 4, lower graph) was calculated as

\[ SI = \max_{j} |c_{x}(j)| \]

where \( j \) is the angular lag between the 2 highest peaks of the crank torque profile taken over 1 pedaling cycle of 360°. The higher symmetry is as it approaches the maximum value of 1, the higher the side symmetry in torque generation during cycling movement.

The polynomial regression and interpolation of the cadence and the torque to 1° crank angle of the pedaling cycle for the 30-second periods corresponding to each subject and condition were averaged together, yielding 1 cadence and torque profile (see fig 4). By taking the mean value over the cycle, 1 observation of the power resulted for each subject and condition (FES, FMS, no stimulation). Roughness and symmetry were similarly processed for the stroke group.

**Statistical Analysis**

The isometric torque evoked and the power generated by electrical and magnetic stimulation were compared. Additionally, volitional and combined (electrically + magnetically) stimulated torques were considered for the stroke group, as well as the smoothness and symmetry of pedaling in electrical and magnetic stimulation conditions. Statistical comparisons were made in the stroke group with the 1-way repeated-measures analysis of variance test with the stimulation mode as factor (FES, FMS, no stimulation) and in the SCI group with the paired \( t \) test. Post hoc multiple comparisons in the stroke group were based on the Tukey honestly significant difference criterion. To determine the individual torque response variability to stimulation, linear correlation was used. Comparisons and correlation were considered significant at \( P<.05 \).

**RESULTS**

**Isometric Measurements**

**Stroke group.** Significantly more torque was produced volitionally (100%) than electrically (11%) or magnetically (27%) on the affected side of the study participants (\( P<.001 \); fig 5). Magnetically evoked torque evoked at 100% stimulation intensity was in all subjects higher than electrically evoked torque (at 62±33mA intensity). Figure 2 illustrates the complete stimulation protocol for a representative patient with stroke. FES produced a maximal isometric torque of about 7.5Nm at a stimulation intensity of 75mA. Using FMS, the torque achieved was about 15Nm at 100% intensity. Combined application of FES+FMS evoked 20Nm torque—that is, the deviation from the sum of torques (15+7.5=22.5Nm) amounts to only about 10%, showing that a summation effect of FES and FMS occurred. The torque produced by FES during combined stimulation showed some decay (about 30% in 50s) caused by fatigue.

As a group, magnetic torque was significantly higher than electrical torque (13.4±3.8Nm vs 5.5±1.73Nm; \( P<.05 \); see fig 5). Investigation of individual response variability showed that a moderate correlation (\( r^2=0.53; P<.001 \)) existed between electrically and magnetically evoked torque. The sum of electrical and magnetic evoked torques did not significantly differ from the combined (electrical + magnetic) torque (\( P=.11 \)).
SCI group. Magnetically evoked torque (at 100% stimulation intensity) was in all subjects less than electrically evoked torque (at 127mA intensity). While considerable fatigue occurred during continuous electrical stimulation at 127mA (causing electrically evoked torque to vanish), typically positive torque pulses evoked by additionally pulsed magnetic stimulation at 100% occurred (see fig 3). In a group comparison, FMS produced significantly less isometric torque than FES (11.86±3.2Nm vs 16.6±3.5Nm; P=.003). Assessment of individual response variability showed that electrically and magnetically evoked torques correlated well ($r^2=0.71$; $P<.001$).

In some patients, maximal FMS bursts applied additionally to the FES produced negative break-ins instead of positive peaks.

In the group comparison, the sum of electrical and magnetic evoked torques differed significantly from the combined (electrical + magnetic) torque ($P<10^{-4}$).

Ergometric Measurements

Stroke group. Power generated during volitional and supported cycling (by FES and FMS), amounted to 51.5±22.4W, 53±21.7W, and 55.2±23.4W, respectively. Power did not show significant dependency on the cycling modality ($P=.79$ in the analysis of variance test).

In contrast, in a comparison of the symmetry and the smoothness of cycling with FMS versus volitional and also FES, most subjects showed improvements both in symmetry (24 and 24 of 29, respectively) and in smoothness (27 and 21 of 29, respectively). In the case of the representative subject exemplified in figure 4, the right-sided hemiplegia caused asymmetrical torque production during purely volitional cycling (symmetry=0.07). Supportive FMS on the right side led to a larger symmetry (0.21). Smoothness improved, decreasing from 44 without FMS to 21 with FMS.

Likewise, the smoothness of cycling in a group analysis (volitional, 56±13.73; FES, 49±14.26; FMS, 40±11.97) was significantly improved ($P<.001$) by FMS support. It did not significantly improve ($P=.65$) with FES support compared with volitional cycling. Moreover, FMS-supported cycling was significantly smoother than FES-supported cycling ($P<.05$).

As the smoothness improved, the symmetry increased significantly under FMS-supported cycling (0.15±0.02) compared with volitional cycling (0.09±0.02; $P<.001$) or FES-supported cycling (0.13±0.03; $P<.05$).

SCI group. Although contiguous and smooth pedaling could be achieved in all subjects by magnetic stimulation (see fig 1), less power was generated with FMS than with FES in all cases. Correspondingly, significantly less power was produced with FMS (2.61±0.88W) than with FES stimulation (7.2±2.75W; $P<10^{-4}$; fig 6). This is in line with the observation that less torque is generated by FMS than FES stimulation in fresh or moderately exhausted muscle.

DISCUSSION

Stroke group. The first important finding of this study is that under our conditions (devices, parameters, stimulation sites), magnetic stimulation supports more effective cycling (in terms of more torque production and better dynamic parameters of cycling like smoothness and symmetry) of subjects with poststroke hemiplegia than electrical stimulation does. This is a result of the partially or completely preserved sensibility in these subjects, which hinders the application of FES more than that of FMS.

Torques evoked by FES and FMS amounted in average to 5.5Nm and 13.4Nm, respectively. Therefore, the ratio of FES-generated and FMS-generated torque in the stroke group is comparable to a similar ratio found in 17 healthy persons by others (mean isometric peak torques evoked by FES and FMS amounted to 4.4Nm and 9.5Nm, respectively).

While the FMS-produced torque represents a significant increase of the volitional torque (volitional + FES compared with volitional; $P<.05$), this is not true for the FES-produced torque. The magnetically and electrically produced torques correlated only moderately ($r^2=0.53$) because subjects do not respond to both stimulation modes in the same manner. One can speculate that the torque-producing capability depends on the subject’s muscle “intrinsic torque capacity,” which also on the pain tolerance of each subject.

In the ergometric experiment, the power did not increase significantly with any stimulation support. From the viewpoint of kinematic analysis, one would expect a smoother and more symmetrical pedaling with stimulation than without. However, this was achieved only with FMS, presumably because of the higher torques produced with magnetic stimulation.

The summation effect of combined stimulation (FES+FMS), which we observed in the quadriceps musculature of some subjects with stroke, could be interpreted as an additional torque produced by a new, fresh pool of muscle fibers being mobilized by additional magnetic stimulation (see fig 2). A similar summation effect was described earlier in a healthy population who received stimulation of the ulnar nerve in a combined (FES+FMS) manner. Therefore, such combined stimulation could be a means to improve mechanical output in patients with preserved sensibility.

SCI group. Although magnetic stimulation–propelled cycling was possible, it was less effective than electrical stimulation in terms of torque and power-generating capability.

In the combined stimulation (FES+FMS) produced torque, the contribution of FES was more important than the contribution of FMS in the fresh muscle of the SCI group (see fig 3). This was the opposite of the situation found in the stroke group, where FMS made the main contribution of torque (see fig 2). This is explicable in terms of the decay of the electrical field with distance; the decay is less pronounced if induced by magnetic stimulation than by surface electrodes. Thus, muscle tissue can be stimulated at a greater depth with magnetic stimulation. Because a summation effect could be shown in the SCI group, we propose that only a few deeper, fresh muscle parts could be mobilized by adding magnetic stimulation to electrical stimulation (see fig 3). Moreover, the occurrence of negative peaks suggests that parts of the antagonistic muscle were activated by FMS. The muscle tissue
stratification and thickness that affect penetration depth of FES and FMS stimulation are presumably different in patients with chronic SCI and chronic stroke.

Because both magnetically and electrically produced torques in persons with complete SCI correlated well ($r^2=0.71$), contrary to the stroke group, they presumably respond to both stimulation modes in a more similar manner. Perhaps their torque-producing capability depends mainly on the subject’s muscle “intrinsic torque capacity.”

**Experimental Setup**

Fixed stimulation sequences (FES and FMS) were designed for subjects with stroke and subjects with SCI, respectively, thus allowing isometric measurements with FES, FMS, and combined stimulation (FES+FMS) during the same session. Because the interventions were not assigned to each subject in a random order in the isometric measurement protocol, interference effects, mainly fatigue, had to be considered. The rationale of the stimulation protocols used is based on our observations made in preliminary experiments that FMS (FES) evoked higher torques than FES (FMS) in subjects with stroke (SCI). Therefore, the adopted stimulation protocols decreased the studied effect rather than increased it.

**Stimulation Conditions**

The results of the present study strongly depend on the electrical and magnetic stimulation conditions used. These factors can influence the torque produced and the pain perceived during FES.

While selecting stimulation parameters, one has to consider that the present study focused on optimization of stimulation-induced movement (particularly cycling) rather than solely on maximization of isometric torque. Therefore, torque has to be maximized and fatigue and discomfort minimized at the same time. While the literature is equivocal on the choice of an optimal frequency of FES of the lower extremity regarding isometric force and sensed discomfort (eg, 25Hz, 30Hz, and 30Hz), the use of 20Hz seems to be well founded.

Moreover, previous work performed in our laboratory on the FES cycling of persons with complete paraplegia showed that a stimulation of 20Hz was superior to higher frequencies for average power produced during cycling. This is because higher frequencies cause more rapid fatigue. Furthermore, technical limitations of the magnetic stimulators require use of 20Hz stimulation. Therefore, this frequency was adopted during both electrical and magnetic stimulation. Other parameters were set to provide maximal mechanical output according to our laboratory standard (FES pulse shape, maximal amplitude and width, coil placement) or fixed at today’s technical standard (FES induction shape, width, maximal amplitude).

Electrode size and placement was similar to specifications in the literature but differed from others. We favored this localization because it was in accordance with our previous work, however, it might have influenced our results. Further, current induced by magnetic stimulation is strongly dependent on both coil shape and orientation. While 2 kinds of coils are in use (circular and figure 8-shaped coils), the latter cannot be used in deep muscle stimulation because of the strong focalization of the induced eddy currents. To achieve mechanical output that overcomes realistic drive resistances, deep musculature like the quadriceps has to be stimulated relatively homogeneously, using a larger coil size, like the 90-mm diameter circular coil. Moreover, a combination of large circular coils (or perhaps elliptical or coils wrapped around the muscle) with decreased muscle selectivity and mechanically constrained trajectories of the legs (as in cycling) seems to be an adequate application of magnetic stimulation. Another benefit of magnetic stimulation is that no direct skin contact is needed, unlike electrical stimulation, and therefore the patient can remain clothed during treatment.

**CONCLUSIONS**

The results of this study suggest that magnetic stimulation is a potential alternative to surface electrical stimulation of the large thigh musculature with regard to stimulation-supported cycling of patients with partially or completely preserved sensibility (with, for example, poststroke hemiplegia or multiple sclerosis). While the present study compared the biomechanical efficacy of magnetic and electrical stimulation, further studies have to be performed to determine whether long-term repetitive application of magnetic stimulation is therapeutically more advantageous than electrical stimulation.

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**References**


**Suppliers**

a. Flextrode 4.5×9 cm² rectangular self-adhering electrodes; Krauth + Timmerrmann Ltd, Poppenbütteler Bogen 11, 22399 Hamburg, Germany.

b. Motionstim 8 channel stimulator; Krauth + Timmerrmann Ltd, Poppenbütteler Bogen 11, 22399 Hamburg, Germany.

c. Magstim Rapid stimulator with Booster Setup; Magstim Co Ltd, Spring Gardens, Whitland Carmarthenshire, Wales, United Kingdom, SA34 OHR.

d. P-Stim 160 magnetic stimulator; MAG & More GmbH, Theresienstrasse 90, 80333 München, Germany.

e. Round magnetic coil (large HP 90); Magstim Co Ltd, Spring Gardens, Whitland Carmarthenshire, Wales, United Kingdom, SA34 OHR.

f. T30FN torque wave; Hottinger Baldwin Messtechnik Ltd, Am Tiefen See 45, D-6100 Darmstadt 1, Germany.

g. AC-servomotor MR 7434; ESR Pollmeier Ltd, Lindenstrasse 20, 64372 Ober-Ramstadt, Germany. servo-controller TrioDrive, ESR Pollmeier Ltd, Lindenstrasse 20, 64372 Ober-Ramstadt, Germany.

h. Matlab v. 6.1.0; Mathworks Inc, Natick, 24 Prime Park Way, MA 01760-1500.