ADJUSTMENT OF FUNCTIONAL ELECTRICAL STIMULATION (FES) ACCORDING TO KNEE FLEXION ANGLE

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To clarify the different results of our simulation and FES-cycling tests, measurements on a knee dynamometer were made. The m. quadriceps of 16 healthy test persons was activated both by FES and voluntary contraction. Stimulated with the same level of intensity in a knee flexion angle range from 5° to 105°, the diagrams showed a very unusual course. The knee torque shows its maximum at the knee flexion angle of approx. 30°. Additional isometric measurements using stimulation intensity on constant on-verge-to pain levels for different knee angles were made. The measured courses of the resulting knee torque as a function of the knee angle are much closer to the results of physiologically activated muscle. These measurements show that for optimum power release, the stimulation intensity must be regulated depending on the knee flexion angle.

KEY WORDS: FES, knee torque, spinal cord injury, knee dynamometer, knee flexion angle

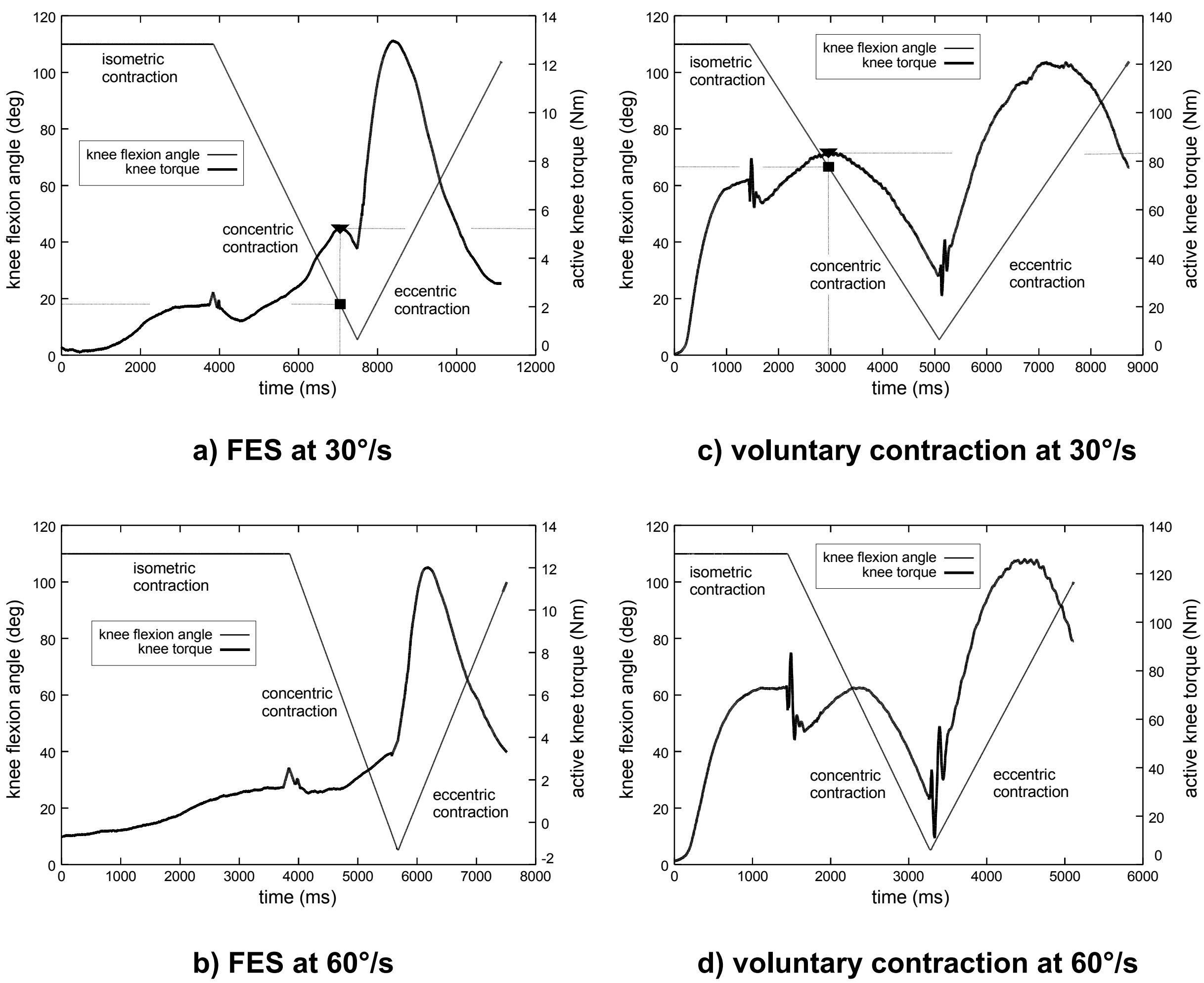
INTRODUCTION: The loss of voluntary muscle control below the spinal cord lesion limits mobility of the spinal cord injury (SCI) subjects. Patients get atrophy of the muscle, bone demineralisation, decubitus, ulceres, heart disease and general loss of cardiopulmonary fitness. Paraplegics are able to use a bicycle by means of Functional Electrical Stimulation (FES). The aim of this study was to find the cause of the discrepancy (deviation) between the simulation (Gföhler et al., 1999) and the measurements (Angeli et al., 1998) of cycling for paraplegics. Schutte et al. (1993) published the muscle joint torques dependent on the knee flexion angle for the isometric contraction by FES for paraplegics. But the isometric muscle joint torques are only relevant to start cycling. Stein et. al. (1999) measured knee torques on both SCI subjects and healthy persons in motion. Their results of the voluntary contraction were quite reproducible, while the amplitudes resulting from stimulated contraction decayed substantially between trials. To get parameters for the simulation of the cycle movement we measured the knee torque at different angular velocities. As the m. quadriceps is basically responsible for the power output (Angeli, 1996; Pawlik, 1995), we chose this muscle for the measurements.

METHODS: 16 healthy persons (8 female, 8 male, mean=32,4 years) who had not been treated with FES before have been tested. The measurements were made on a knee dynamometer, that was developed at our institute (Angeli, 2000). Four surface electrodes (rectangular self adhesive electrodes, 50x130 mm) have been placed on the motor points of the m. quadriceps and the muscle was stimulated by the programmable stimulation unit 'Compex Sport p'. The stimulation frequency was 30 Hz. This low stimulation frequency was chosen to reduce muscle fatigue. The amplitude of the stimulation current gradually ramps up to and down from a plateau level (compare Schutte et al., 1993). Without the ramps the spasms increased. At first the test person's quadriceps is warmed up for ten minutes. The stimulation intensity was chosen individually for each test person depending on their pain sensitivity at a knee flexion angle of 15°. It is necessary to extend the leg almost completely, as in this position the pain sensitivity is at its maximum. The individual stimulation intensity levels attained in this manner had the effect that none of the test persons suffered from pain during tests. After getting familiar with the test procedure, measurement cycles (Table 1) were done on two different days. These measurement cycles consisted of FES and voluntary physiological stimulation. For both stimulation types measurements were made for isometric, concentric and eccentric contraction. For the calculation of the active knee torque the passive knee torques (inertia force and mass moment of inertia, joint torques from passive muscle forces) had to be subtracted from the total measured torque. For example: to hold the leg at the knee flexion angle of 5° the m. quadriceps must overcome the weight of the shank and foot and the passive torque of the antagonist muscles (hamstrings, m. gastrocnemius and others).

Table 1 Measurement Cycles

cycle	1	2	3	4	5	6	7	8	9	10	11	12	13
start angle	110°	110°	110°	110°	110°	110°	105°	91°	75°	61°	45°	31°	15°
end angle	5°	5°	5°	5°	5°	5°	104°	90°	74°	60°	44°	30°	14°
angular velocity	15°/s	30°/s	60°/s	90°/s	120°/s	180°/s	1°/s	1°/s	1°/s	1°/s	1°/s	1°/s	1°/s

RESULTS AND DISCUSSION:



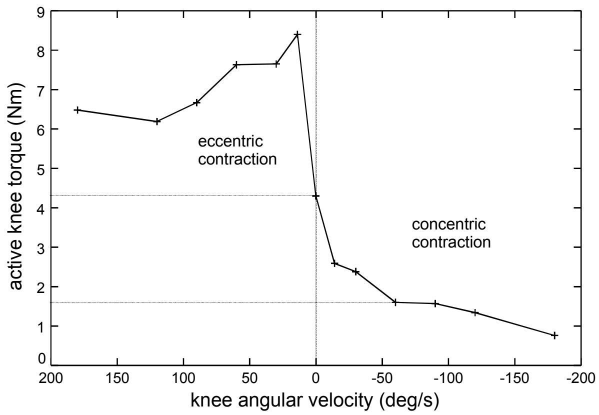
a) FES at 30°/s

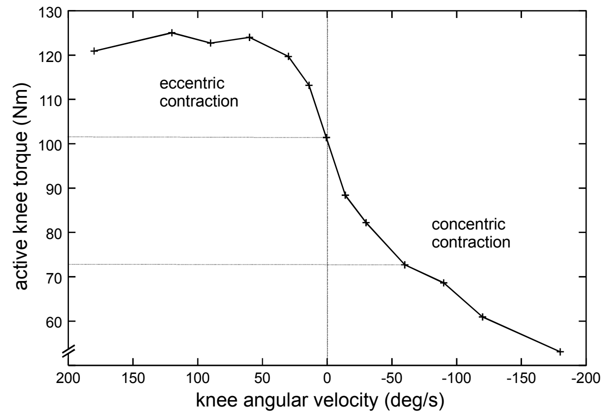
c) voluntary contraction at 30°/s

b) FES at 60°/s

d) voluntary contraction at 60°/s

Figure1 a) to d) - Active knee torque and knee flexion angle as functions of time; averaged results of all test persons (both legs, both test days); maximum knee torque ▼ in concentric contraction at the knee flexion angle (marked with ■) at 30°/s.



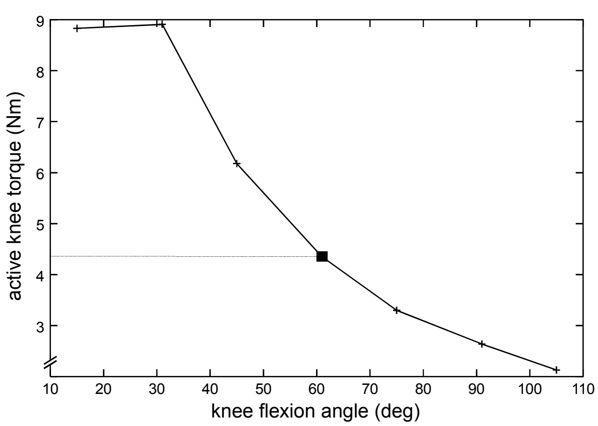


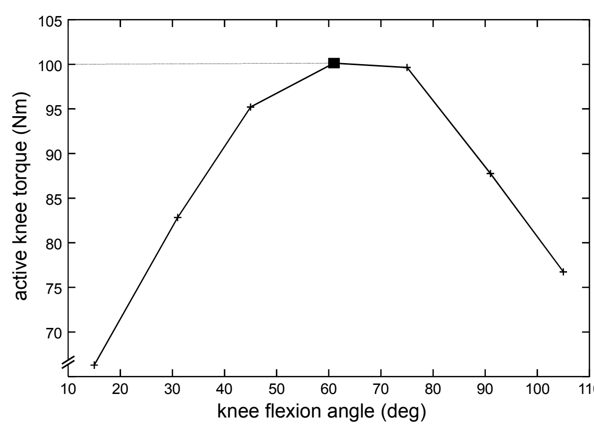
When comparing the results, it becomes evident that the knee torques of the FES contraction measurements (fig. 1 a – b) are clearly lower than the knee torques measured with voluntary contraction (fig. 1 c – d). This applies for both isometric and concentric contractions. The peak

a) Contraction by FES **b) Voluntary contraction**

Figure 2 - Knee torque as function of knee angular velocity at a knee flexion angle of 60°; averaged results of all test persons.

knee torque obtained by FES is reached at clearly lower knee flexion angles when contracted concentrically. This could have to do with the adjustment of the stimulation intensity at this angle range (see Methods). The diagram (Fig. 2 a; FES) shows knee torque over contraction velocity differs greatly to the force velocity relation of activated muscle tissue (Zajac, 1989). Voluntary contraction shows a similar course to the force velocity relation of activated muscle tissue. It is striking that the measured torque declines during rise of the flexion angular velocity in the eccentric contraction by means of FES. At the knee extension velocity of 60°/s during voluntary concentric movement over 70% of the isometric knee torque is reached (see Fig. 2 b). Less than 40 % of the isometric knee torque achieved by FES is obtained at the same knee angular velocity.

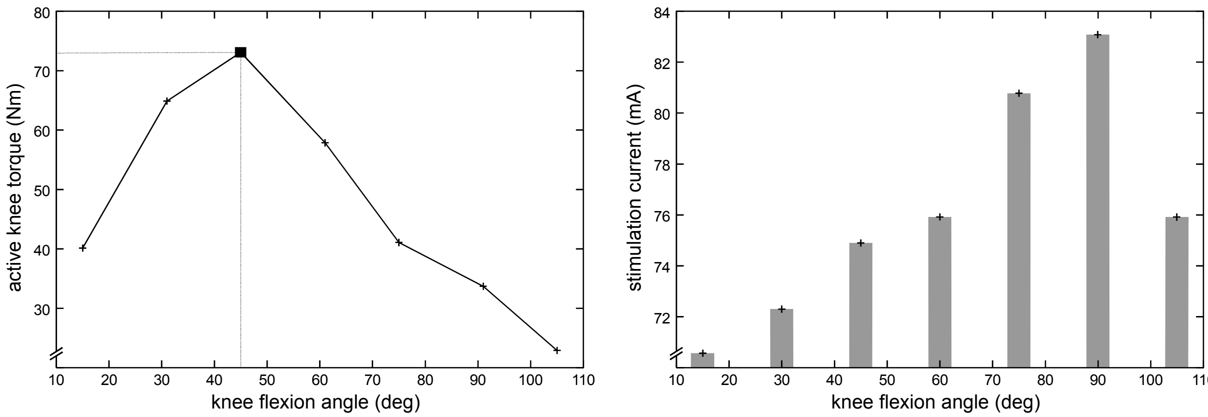




a) Contraction by FES **b) Voluntary contraction**

Figure 3 - Isometric active knee torque as function of the knee flexion angle with constant stimulation intensity; averaged results of all test persons; knee torque at the knee flexion angle 60° marked with (■)

The course of torque in fig. 3 a) is not explainable with the current available muscle models. The EMG activity over the knee angle in fig. 3 b) is not constant (Bochdansky et al., 1990). These two observations prompted us to repeat the isometric measurements alternatively in a second test cycle with six test persons (two females and four males; the average age was 28,0 years). This time knee torques were measured isometrically at 7 different knee flexion angles. The other difference to the first test cycle was, that the stimulation intensity was adjusted to the maximum individually for each test person and at each knee flexion angle as done at 15° in the first test cycle (fig. 4 b). From the group of 16 the 6 test persons with the lowest pain sensitivity were chosen so that high stimulation intensity levels could be used. The resulting course of active knee torque over knee flexion angles (fig. 4 a) has a greater resemblance to that of voluntary contraction. The difference between the two is their maxima; being at 45° knee flexion angle with FES (second cycle) in comparison to 60° with voluntary contraction.



a) Contraction by FES **b) Stimulation current**

Figure 4 - a. Isometric knee torque as a function of knee flexion angle with subjectively adjusted stimulation intensity; averaged results of 6 test persons; maximum knee torque at the knee flexion angle of 45° (marked with ■); fig. 4 b. Subjectively adjusted stimulation current as a function of the knee torque; averaged results of six test persons.

CONCLUSION: In present applications of FES the knee flexion angle is read by the control unit in order to protect the lower extremity against knee hyperextension. It is necessary to vary the stimulation intensity according to the knee flexion angle to obtain optimal power output with FES. To achieve this, it will be necessary to develop stimulation units that are able to read the knee flexion angle and adapt the stimulation intensity accordingly.

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