Development of an optimized pedal path by using Functional Electrical Stimulation

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Introduction

The aim of this study was to develop a special optimized pedal path to be used on an exercise-tricycle for paraplegics.

Cycling as a means for training with Functional Electrical Stimulation (FES) for paraplegics has been studied by various authors. Three- and four-wheeled cycles have been developed (Mayr, 1992; Petrofsky et al., 1983; Petrofsky & Smith, 1992). The stimulation patterns for the stimulated leg muscles have been optimized in various ways (Gföhler et al., 1998). Theoretical investigations have been carried out to optimize the geometrical position of rider and crank axis (Schutte et al., 1993). However all these investigations have one thing in common: they assume a standard bicycle drive-unit with a circular pedal path. Angeli (1996) proved that the circular pedal path is not optimal for pedaling for healthy persons. The average power output can be raised using different optimized paths. As paraplegics with FES only use a very limited number of muscles/muscle groups for the development of active force (mostly 3 or 4 ) it seems even more likely that different pedal paths will contribute to raise the average drive power.

Methods

The aim of this treatise was to realize the optimal drive as derived from a simulated calculation (Pawlik, 1995).

This simulation program was already used for the simulation of the lower extremities’ movement of healthy persons. Compared to Pawlik (1995) the effective lever arm in the knee joint has been changed to averages from Chow et al. (1999) and Pawlik (1995) in a knee angle between 0° and 120°. According to the geometrical position of the patient’s leg in the movement and the physiological function of the muscles/muscle groups, gluteus maximus, hamstrings and quadriceps have been chosen for the surface stimulation as well as the muscles/muscle groups activated by the peronaeus reflex: tibialis anterior, hamstrings and iliopsoas. As the ankle joint is fixed, the muscle tibialis anterior generates no power.

A musculoskeletal model of the lower extremity contributed to the optimization of the pedal path, which is realized by a four-bar linkage (Figure 1) and a test bed was developed to examine the simulation results (Angeli, 1998).

![Figure 1: Four-bar linkage for optimized pedal path](image-url)
As all paraplegics should drive with the same pedal path, the pedal path for an average person was calculated and reduced to the smallest patient of the test group. Since the smallest patient could not pedal a crank length of 170 mm, the calculation of the construction’s dimensions have been matched to a crank length of 165 mm.

It is impossible for paraplegics to pedal at high frequencies. Therefore we used a pedal rate of 30 rpm in our simulated calculation. Power output measurements of the single muscles/muscle groups on the circular path have been undertaken. The peroneus reflex generated a much smaller power output than the other muscles/muscle groups.

Figure 2 shows the simulated activation pattern of each stimulated muscles/muscle groups on the optimized pedal path at 30 rpm individually. The vastii of the quadriceps are the main muscles responsible for the power output during the pedaling motion. The measured activating pattern is represented by the dotted line. The influence of the biceps femoris short head is so small that we only considered the rest of the hamstrings for the stimulation of the hamstrings. The peroneus reflex activates the muscle iliopsoas and the muscle group hamstrings simultaneously. Because the peroneus reflex activates the muscle group hamstrings and the muscle iliopsoas at the same time there is a part of the pedal movement in which both muscle/muscle group work antagonistically. The appropriate stimulation angle for the peroneus reflex is small because the hamstrings are stimulated independently in the angle range in which the iliopsoas would work antagonistically.

**Figure 2:** Stimulated activation pattern for the muscle/muscle group quadriceps, gluteus, hamstrings and the peroneus reflex at 30 rpm on the optimized pedal path (dotted lines: measurement results, thick lines: stimulated muscle group, thin lines: individual muscles)

The development of the four bar linkage was based on the calculations of the circular pedal path. Results of further calculations made us expect an 8.8% power output increase with the four-bar linkage construction.
But during tests several patients got spasms on the common circular pedal path, possibly in consequence of the large hip angle range. Because of this problem we reduced the hip angle range by adapting the four-bar linkage. This linkage enables the same power output as the circular path but has a reduced hip angle range of $47.3^\circ$ as against $51.5^\circ$ at the circular path. The four bar linkage was attached on the test bed, because the comfort of the patients and a more natural motion was more important to us than an additional power output. The patients got less spasms during the tests and felt more comfortable with this path.

The results of the test bed measurements were compared to those of the simulation. Due to the more appropriate joint angles paraplegics feel more comfortable at higher pedaling frequencies on this new pedal path. Depending on the patients’ leg length, the power output on the optimized noncircular pedal path can be higher than on the circular pedaling path.

**Conclusion**

Although simulation and measurements have shown good results it still has to be investigated how strongly the results are influenced by individual parameters:

- condition of the patients’ muscles,
- stimulation conditions (position of electrodes, nerve volume reached by the electrical field),
- occurrence of spasms.

**References**


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