# Modeling the activity of daily life -relevant functional output of FES cycling: an experimental study

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## Abstract

***Purpose:** This study expands on connections between laboratory measurements and "in field" performance of persons with complete spinal cord injury (SCI). It explores whether a regression model incorporating the conditional abilities, muscle force and endurance limit, can predict the distance that untrained SCI individuals can cover during outdoor FES cycling.*
***Methods:** One trained and six untrained subjects with complete SCI participated. Isometric moment profiles of the six stimulated muscle groups were determined with a special setup that measured torque. Endurance was measured during FES-propelled ergometer exercise tests. Covered distance and cadence data were collected during outdoor FES-cycling tests. Subsequently, local muscular fatigue was computed from measured torques, cadences, and endurance limits. Finally, the relationship between fatigue rate and distance covered until subject exhaustion was measured by correlation and regression analysis.*
***Results:** The correlation analysis of cycling distance yielded highly significant determination coefficients of 0.92 for fatigue resistance and 0.86 for cycling capability (p<0.01).*
***Conclusion:** Since the determination coefficient for the correlation of isometric torque and distance amounted to 0.74 (p<0.01), inclusion of the endurance limit in the regression model of distance(as defined by fatigue resistance or cycling capability) reduces the unexplained rest variance by 0.92-0.74=0.18 and 0.86-0.74=0.12, respectively. Thus, a composite score for muscle fatigue rate including force and endurance describes the cycling performance of untrained SCI subjects better than a score including only force, because both force and endurance are independent determinants of FES cycling.*

## 1. INTRODUCTION

If outdoor FES cycling is to be used for recreation, mobility, or fitness in daily life (ADL), the SCI cyclist must be able to cover minimally 10 km, to travel at a speed of at least 6-7 km/h, and to pedal smoothly [1]. Training is of decisive importance therefore, the comprehension and management of this training process must be based on a physiological model that predicts the ADL-relevant functional output of FES cycling.
To build such a model, a measure of the functional performance outcome (the distance covered in case of outdoor cycling) has to be correlated with the conditional abilities, force and endurance limit, measured in the laboratory. The relationship between distance, force, and endurance has to be explored in untrained, chronic, complete SCI subjects. To establish this relationship, two hypotheses were proposed. First: covered distance is dependent only on the local muscular fatigue state, and second: maximal isometrical force and endurance limit determine the local muscular fatigue state. Consequently, force, endurance limit, and functional output were determined in isometrical torque measurements, indoor ergometer pedaling, and outdoor cycling tests, respectively.

## 2. METHODS

Seven subjects with complete spastic SCI were recruited. The untrained subjects (no. 1-6 ) with lesions at levels T4-12 had no previous FES training under load, except for training sessions performed in the outpatient clinic. An exceptionally well-trained chronic SCI subject (no. 7), lesion level T6, who had FES training under load for 18 months, also participated . Each participant finished 4 ergometric and 3 outdoor cycling sessions; a supplementary session was also scheduled for the isometric measurements. For all subjects the ergometric and outdoor cycling sessions in the outpatient clinic consisted on the average of 1.5 hours of pedaling with 2-3 10-minute breaks between the work phases. The cycling stimulation setup consisted of 20 Hz frequency, I=0-99 mA, and PW=500 usec. First, the individual torque profiles (crank torque vs. crank angle) of the six stimulated muscle groups (quadriceps, gluteus, hamstrings) were determined for all patients with a torque sensor (ATI, Garner, USA) mounted on a stationary tricycle.

The cycling situations of the patients are characterized by cadence and muscle stress. The muscle stress $k$ is computed with the formula $k = Load / Drive$, whereas $Load$ is provided essentially by the drag torque and the crank revolution speed, and $Drive$ is the averaged isometrical torque.

Indoor cycling exercises on the ergometer (Motomed Viva 1, Reck GmbH, Betzenweiller, Germany) were used to find cycling situations (cadence, muscle stress) that could be continued for at least 20 minutes without reducing the cadence by more than 10 rpm (no local fatigue) by constant resistive torque. These situations were assumed to occur at the endurance limit.

In subsequent outdoor cycling exercises (OVG tricycle, Munich, Germany) cadence, drag-torque, and distance to exhaustion were recorded for each subject, who freely chose the cycling situations. A graphical representation of the cycling situations allowed a definition of the individual endurance limit of the paraplegic. The steady-state region was separated from the fatigue region by means of the least squares method on the basis of limit points obtained in the ergometer trials (Fig.1).

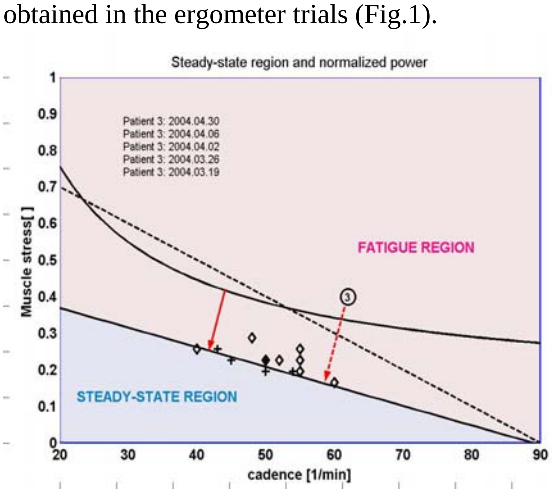


Fig.1 Derivation of the endurance limit of patient 3. Diamonds represent ergometer exercise tests during which revolution speed was maintained at least 4 minutes; later it was less. Crosses show steady-state ergometer tests performed at a constant revolution speed for at least 20 minutes. Solid straight line: “paraplegic” borderline, dashed line: “normal” borderline, solid curve: normalized power. The outdoor cycling situation is represented by the encircled figure 3. Arrows represent the fatigue rate for the cycling situation (dashed) and for the cycling capability of the patient (solid).

The region delimited by the normalized power, given by $k \times \omega$ (muscle stress times rotation speed of crank), is the area in which outdoor cycling of the individual patient on the particular OVG tricycle has to take place. The distance of the outdoor cycling situation from the endurance limit was called according to our second hypothesis, the *fatigue rate* (inverse: *fatigue resistance*). The fatigue rate accounts for the stress and cadence decay from the actual cycling situation until the endurance limit. Likewise, the distance between the normalized power curve and the endurance limit is the *minimal fatigue rate* (inverse: *cycling capability*) of the individual with respect to the particular tricycle.

According to our first hypothesis, the fatigue rate and the cycling capability must correlate with the distance covered until exhaustion.

## 3. RESULTS

### 3.1 Endurance limits

Application of the geometrical method illustrated in Fig.1 gave the endurance limits of the SCI subjects 1-7 ( Fig. 2). The endurance limits of the untrained subjects 1-6 form a compact bundle of straight lines, all flatter than the normal endurance limit (Fig.2). We have shown further, that endu-

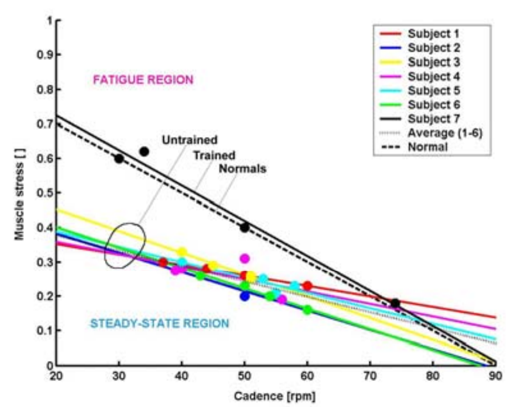


Fig.2. Endurance limits of SCI subjects (1-7) and able-bodied persons.

rance limits of most untrained subjects differ significantly from those of able-bodied persons. The endurance limit of well-trained subject is practically identical to the normal endurance limit.

### 3.2 Cycling capability of SCI subjects with different strength

The relative position of the endurance limit and the specific power curve characterizes the FES-cycling capability of the individual SCI subject (Fig.3). It permits conclusions to be drawn about cycling capability. For example, as the endurance limit and specific power of untrained subject 5 did not cross, cycling is only possible in the fatigue mode. The driving situation of subject 5 is actually located in

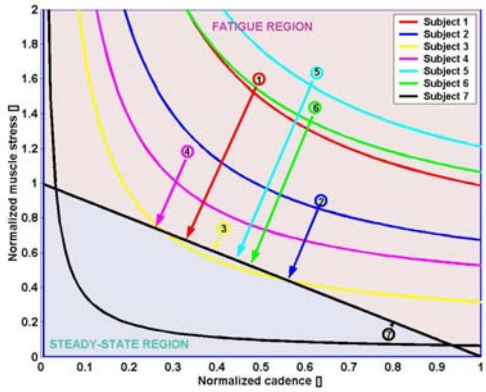


Fig.3. Endurance limits (scaled to the same straight line), specific power curves (curves), and cycling situations (operating points are indicated by circled numbers) of the study participants in the normalized stress-cadence plane. Arrows mark the fatigue rates corresponding to operating points.

the fatigue mode region. In contrast, the endurance limit and specific power curve of untrained subject 3 cross to form an area of intersection within the steady-state region. Optimally, the cycling situation (operating point) should be located in this area, i.e., steady-state cycling is possible. Although the experimentally recorded cycling situation of subject 3 is located in the fatigue region, there is thus room for technical improvement. A large area is formed by the intersection of the endurance limit and specific power for the extraordinarily well-trained subject 7. Thus, the cycling situation (operating point 7) is located below the endurance limit, and cycling takes place in the steady-state mode. In fact, Fig. 3 depicts the conditional abilities of the subject: force (specific power) and endurance (endurance limit). Force or endurance training would lower the specific power or raise, respectively, the endurance limit, thus both increasing the area of intersection.

### 3.3 Correlation between fatigue resistance and covered distance

Fig. 4 shows the fatigue resistances in outdoor cycling situations, the cycling capabilities, and the isometric torques (average of positive sum over a full crank revolution) vs. the covered distances. Correlation analysis with cycling distance to exhaustion resulted in high determination coefficients of 0.92 and 0.86 for fatigue resistance and cycling capability, respectively. Both correlations were highly significant ($p<0.01$). Since the determination coefficient for correlation of the isometric torque with the distance amounts to 0.74 ($p<0.01$), inclusion of the endurance limit as defined by fatigue resistance or cycling capability reduces the unexplained rest variance by

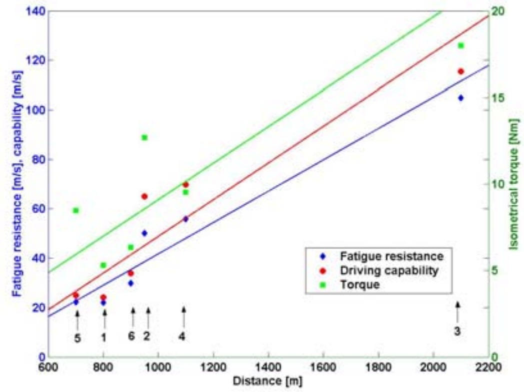


Fig. 4. Scatter plot and linear regression of fatigue resistance, cycling capability, and isometric torque vs. distance covered during outdoor cycling of subjects 1-6. Figures in the lower part of the graph denote data of the respective subjects.

0.92-0.74=0.18 and 0.86-0.74=0.12, respectively.

### 4. DISCUSSION AND CONCLUSIONS

This experimental model of FES cycling revealed the significant dependency of functional outcome of cycling (covered distance) on muscle strength and endurance, as defined by the muscle fatigue rate. Positive correlations between fatigue resistance (or cycling capability) and covered distance given in Fig. 4 were expected: the higher the fatigue resistance, the longer the cycling distance. Structurally analogous relationships are known in the literature for other cyclical human movements, e.g., high performance cycling or running by able-bodied persons. The current study proved that isometric muscle torque and endurance limit explain up to 86-92% of distance variance, whereas muscle torque only accounts for 74%. The endurance limit is probably responsible for only 12%-18% of distance variance, because the regression computations are based on the data of untrained SCI subjects, whose endurance limits differ relatively slightly (Fig. 3). The variability of endurance limit can be expected to make a higher contribution to the variance of distance in reasonably trained SCI subjects.

**References**

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