The Effects of Releasing Ankle Joint on Pedal Force and Power Production during Electrically Stimulated Cycling in Paraplegic Individuals: A Pilot Study

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Abstract— **Previous research has investigated functional electrical stimulation (FES) cycle force and power output (PO) from the perspective of knee and hip joint biomechanics. However, ankle-foot biomechanics and, in particular, the effect of releasing the ankle joint on cycle pedal force and PO during FES cycling in paraplegics has not been widely explored. Therefore, the purpose of this study is to determine whether releasing the ankle joint might influence the peak pedal force and PO during FES cycling in paraplegics. Three complete paraplegics (C7 – T4) participated in this study. All participants performed two sessions of cycling in randomized order. Session 1 and 2 required the participants to cycle in fixed and free-ankle setup, respectively. For each session, the participants performed two sub-sessions of FES cycling. During sub-session 1, the muscles stimulated were upper leg muscles [quadriceps (QUAD) and hamstrings (HAM)]. In sub-session 2, both upper and lower leg muscles [QUAD, HAM, tibialis anterior (TA) and triceps surae (TS)] were stimulated. The normalized peak pedal force and PO of each condition were analyzed. Overall, the normalized peak pedal force and PO during fixed-ankle FES cycling is higher than free-ankle FES cycling. Stimulation of both upper and lower leg muscles during FES cycling provided higher normalized peak pedal force and PO compared to the upper leg muscles stimulated alone. The present pilot study revealed that fixed-ankle FES cycling produced higher normalized peak pedal force and PO than free-ankle FES cycling. Future work involving more paraplegics will be investigated. This finding might serve as a reference for future rehabilitative cycling protocols.**

Keywords— **Functional Electrical Stimulation; Spinal Cord Injury; Cycling; Ankle Movement; Rehabilitation Exercise.**

I. INTRODUCTION

Cycling is a popular exercise modality for individuals with spinal cord injury (SCI). The general goal of cycling exercise is to produce the highest possible mechanical power to maximize the merit of health benefits [1]. In SCI populations, such cycling exercise is artificially evoked by functional electrical stimulation (FES), whereby leg muscles are recruited by electrical pulses delivered on the skin surface overlying key muscles [2, 3]. It has been proven to provide benefits including improved muscle strength, endurance, mechanical power output (PO), skin condition, cardiopulmonary fitness, reversal of muscle wasting, blood flow in the legs, reduced incidence of muscle spasms, body composition, bone mass, quality of life, joint health and flexibility, and offsetting some of the secondary complication [2, 4]. However, how the foot is affixed to the pedal has been of interest. A fixed ankle foot orthosis (AFO) or fixed pedal boot is often deployed to affix the foot to the pedal and this has been widely used to also provide shank stability; thus restricting the leg movements in the sagittal plane during cycling. In the standard setup for FES cycling, the ankle joint is immobilised using an orthosis, and stimulation is applied to quadriceps femoris (QUAD), gluteus maximus (GLU), and hamstrings (HAM) using surface electrodes [2, 3].

Researchers have previously sought to elicit maximum PO during FES cycling in order to increase the benefits of cycling during rehabilitation. Berkelmans [5], Sinclair *et al.* [6], Szecsi *et al.* [7], and Duffel *et al.* [8] have reported that the magnitude of mechanical PO produced during FES cycling in individuals with SCI is very low compare to the PO produced during voluntary cycling in able-bodied (AB). The reasons of the low PO magnitude [7] might be due to the inefficiency of artificial muscle activation, the crude control of muscle groups accomplished by stimulation, and muscle atrophy and transformation due to chronic paralysis and disuse. Consequently, several studies have investigated the origins of cycling PO during FES exercise [3, 9].

Ankle positioning during cycling is one of the more important factors for effective pedaling [10, 11], yet this has not received much previous research attention. Theoretically, the PO can be improved by releasing the ankle joint and adding triceps surae (TS) and tibialis anterior (TA) muscles evoked by neurostimulation [4]. Stimulation of the TS and TA has been investigated before in fixed-ankle FES cycling and no remarkable effect on PO was noted, except that it affected only on the cardiovascular and circulatory responses [12]. The stimulation of the TA and TS in a free-ankle setup shows 14% greater PO than the fixed-ankle FES cycling only with the tuning of contact point between the foot and pedal to the relative strength of the ankle plantar flexors [4]. However, Ferrante *et al.* [13] reported that the calf muscle generates limited knee flexion action due to the presence of orthosis that fixed the ankle angle, which may reduce the maximum PO. In another study, Fornusek *et al.* [14] reported that the free-ankle FES

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cycling with the stimulation of the shank muscles (TS and TA) was found safe and increased the ankle excursions that might have improved joint mobility and prevent contractures in persons with paralysis. Taken together, these studies have further shown the importance of investigating maximum PO as a function of ankle movements during FES cycling in paraplegics.

In contrast, a limited number of studies have investigated AFO-constrained ankle movements on the power production during FES cycling in paraplegics. It is an important concern in the rehabilitation systems to elicit maximum pedal force and PO during FES cycling. Therefore, the purpose of this study was to investigate whether a fixed and free-ankle movement might influence cycle peak pedal force and PO during FES cycling in paraplegics. We hypothesize that free-ankle FES cycling might alter the production of peak pedal force and PO, as the biomechanics are affected by the ankle patterns [15].

II. Materials and Methods

A. Participants

Three complete paraplegics (C6 – T4), two males (38.5 ± 14.8 y and 71.0 ± 12.2 kg) and one female (47 y and 82 kg) participated in this study. All participants provided their written informed consent before taking part in the study. The participants had no previous or ongoing record of neuromuscular, musculoskeletal, rheumatological, cardiovascular disorder or orthopaedic lower limb injuries. All the participants were trained with FES cycling for at least 12 weeks. This study was approved by the local Medical Ethics Committee, University of Malaya Medical Centre, University Malaya, Kuala Lumpur, Malaysia (Ref No.: 1003.14(1)).

B. Experimental setup

A FES cycle ergometer (MOTOmed viva2) was utilised in this study. Self-adhesive gel electrodes were placed over the belly of QUAD, HAM, TA, and TS muscle groups. An in-shoe F-scan system (Tekscan Incorporated, Boston, Massachusetts) was placed under the foot of the participants and connected to a "cuff-unit" that linked the foot sensors to a computer via a 10-m cable. Tight socks were applied on the foot to prevent displacement of foot sensor during cycling. For the fixed-ankle FES cycling, the lower legs of each participant were placed on fixed position (FP) AFO that was fixed to the pedal to restrict the ankle joint movement. The seat position from the crank axle was adjusted and recorded for each participant so that the knee extension did not exceed 150-160° at the bottom dead centre (BDC). Motion Capture System (Qualisys) was used to capture the marker placed at the hip, knee, ankle, fifth metatarsophalangeal joints, crank axle and pedal.

C. Data collection protocol

Testing was conducted in two sessions with two sub-sessions for each session. The first session required the participants to perform FES cycling in fixed-ankle setup with FP AFO and the second session required the participants to perform FES cycling with free-ankle setup. Two modes of cycling were performed for each session; passive cycling (without FES induced leg cycling) and FES cycling (FES induced leg cycling). Sub-session 1 consisted of 1 min passive warm up, 2 min FES cycling with QUAD and HAM stimulated, 1 min cool down, and 10 min of resting phase. Sub-session 2 consisted of 1 min passive warm up, 2 min FES cycling with QUAD, HAM, TA and TS stimulated, 1 min cool down, and 10 min resting phase. The order of each session for each participant was randomized. Each session was separated by at least 48 hours. The participants performed cycling at 50 rpm. The stimulation (300 μs pulse width and 30 Hz frequency) was applied by an 8-channels stimulator (RehaStim ScienceMode, HASOMED GmbH, German).

D. Data processing and analysis

The kinetic and kinematic data for each session was recorded in real time at 120Hz by the software [Tekscan Incorporated, Boston, Massachusetts and Motion Capture System (Qualisys)] to store the data into a PC for offline analysis. Only the last 20 s kinetic and kinematic data of each cycling mode for each session was recorded. The peak normalized pedal force and PO during fixed and free-ankle FES cycling were compared and analyzed.

III. Results

A. Pedal force

Fig. 1 showed the normalized peak pedal force during fixed and free-ankle FES cycling. Fixed-ankle FES cycling with both upper and lower leg muscles stimulated showed the highest normalized peak pedal force (87.5 ± 15.1%). Free-ankle FES cycling with upper leg muscles stimulated alone showed the lowest normalized peak pedal force (58.4 ± 11.5%).

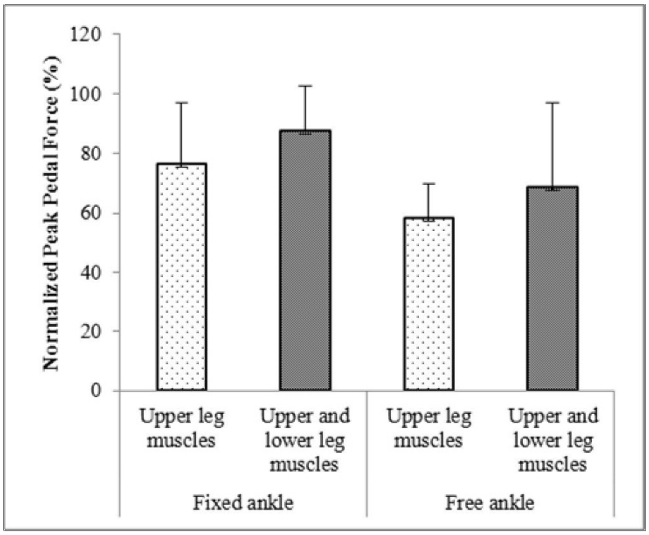

Fig. 1 Normalized peak pedal force (%)

B. Pedal PO

Fig. 2 showed the normalized peak pedal PO during fixed and free-ankle FES cycling. Fixed-ankle FES cycling with both upper and lower leg muscles stimulated showed the highest normalized peak pedal PO (89.9 ± 14.4%). Free-ankle FES cycling with upper leg stimulated alone showed lowest normalized peak pedal PO (54.2 ± 4.3%).

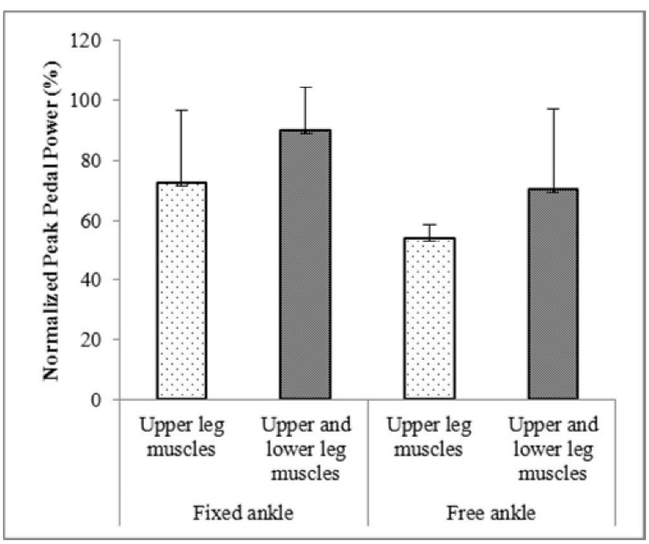

Fig. 2 Normalized peak pedal PO (%)

IV. DISCUSSION

The present study sought to investigate possible differences in normalized peak pedal force and PO generated during fixed and free-ankle FES cycling. To our knowledge, no studies have yet to investigate the effect of releasing ankle joint on the peak pedal force and PO during FES cycling in paraplegics.

A. Pedal force

Pedal force produced in this study was originated from the stimulated muscles during FES cycling. The normalized peak pedal force revealed in the current study was opposed our initial hypothesis. Fixed-ankle FES cycling showed greater normalized peak pedal force compared to the free-ankle FES cycling, either with and without the stimulation of lower leg muscles. This might be due to the similar stimulation angle used for both the fixed and-free ankle FES cycling in this study. Previous research had shown that the crank angles at which the muscle groups are stimulated were altered by the addition of the lower leg muscles stimulation. Therefore, higher normalized peak pedal force could be produced during free-ankle FES cycling if the stimulation angle was adjusted until optimal performance was achieved. It is important to achieve the highest possible pedal force to maximize the merit of health benefits in paraplegics [1].

B. Pedal PO

The present study also reported that the normalized peak pedal PO of fixed-ankle FES cycling with the stimulation of both upper and lower leg muscles was higher than free-ankle FES cycling. The results refuted our initial hypothesis. Ideally, greater PO was generated from the stimulation of both upper and lower leg muscles. In this study, lower leg muscles was stimulated to allow the ankle joint to move in dorsi- and plantarflexion during free-ankle FES cycling. One of the reasons that the current study revealed a lower normalized peak pedal PO during free-ankle FES cycling was due to the power loss at the ankle joint as the participants often experienced muscle spasms during free-ankle FES cycling. Another reason was the drop in cycling cadence observed during free-ankle FES cycling. Changes in cycling cadence could affect the pedal PO production; low cadence produced low pedal PO production [6]. The present study observed that the free-ankle FES cycling produced non-smooth pedaling to the participants. This non-smooth pedaling would affect the cycling cadence which was highly effected the pedal PO production. Therefore, the best stimulation angle was important in order to produce smooth pedaling and thus, producing maximum pedal PO during free-ankle FES cycling.

V. Conclusions

The pedal force and PO found in this pilot study were higher at fixed-ankle FES cycling compared to the free-ankle FES cycling.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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