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SPECIAL COMMUNICATION

Role of Functional Electrical Stimulation in Tetraplegia Hand Surgery

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Abstract

The use of functional electrical stimulation (FES) to improve upper limb function is an established method in the rehabilitation of persons with tetraplegia after spinal cord injury. Surgical reconstruction is another well-established yet underused technique to improve the performance of the upper extremities. Hand surgery plays an essential role in restoring hand function, mobility, and quality of life in the tetraplegic population. The knowledge about the effects of FES on a structural and functional level is fundamental for understanding how and when FES can be used best to support the effect of hand surgery, both pre- and postoperatively. In this article we discuss principles of FES and how FES improves functional outcome after surgical reconstruction. The reported results are based on preliminary clinical observations.

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Functional electrical stimulation (FES) in rehabilitation of patients with spinal cord injury (SCI) opens up a wide field of possible treatments with multiple aims. FES treatment has been shown to improve lower[1-3] and upper limb function[4-6]; improve trunk function[7,8]; improve breathing in high-level tetraplegia[9-11]; improve bladder, bowel, and sexual function[12]; improve cardiovascular fitness by increasing aerobic capacity[13-16]; decrease body fat mass[17]; and prevent pressure ulcers by increasing muscular blood flow and muscle mass.[18-21] FES may also have an influence on synapses and motor neurons, as animal studies have shown.[22] We also propose that FES could be a useful treatment modality before and after surgical reconstruction of upper limb function.

One of the first applications of FES in combination with tendon transfer procedures was the freehand system, developed in Cleveland, Ohio.[23] The freehand system was implanted in >250 persons with tetraplegia with a C5-6 lesion.[24] It was reported that all patients with implants had better grasp and release, greater pinch force, and activities of daily living independence.[25] To improve the outcome, implanting the system was combined with reconstructive hand and arm surgery. As surgical techniques for reconstructive procedures continue to be refined, the pre- and postoperative rehabilitation protocols are evolving as well. Importantly, the combination of multiple procedures in a single-stage operation has led to shorter and more efficient postsurgery rehabilitation periods.[25-28] Therefore, integrating the use of FES with surgical protocols may be of benefit on a structural and functional level to improve the preoperative condition of the donor and recipient muscles and even more to enhance the postoperative outcome and optimize the rehabilitation process.

The aim of this article is to discuss how and when FES can be used to support the effect of hand and arm surgery in patients with tetraplegia. Preoperative strengthening of the transferred muscle is crucial for a satisfying functional outcome. Depending on the intended postoperative function of a donor muscle, FES may also be used to retrain the transferred muscle postoperatively under certain conditions. We will discuss the use of FES to achieve these goals and present preliminary findings based on our clinical experience.

Effects of FES on muscular physiology

There are a few principles of FES that must be considered in order to configure an efficient/effective stimulation protocol. When creating individual stimulation protocols, the effectiveness of different stimulation parameters should be considered. An increasing current amplitude (mA) leads to an increased torque

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(Nm) by recruitment of additional motor units. Increasing the pulse width has shown to increase the torque (Nm) by increasing motor unit activation. Furthermore, increasing the frequency (Hz) leads to an increased evoked torque (Nm) by increasing the torque per active muscle area.[29]

Activation and recruitment

The stimulation current is transmitted via nerves; therefore, the lower motor neuron (LMN) must be intact.[30] The propagation of action potentials and synaptic transmission occurs analog to the central nervous system. In FES, all reachable motor units are excited without physiological recruitment. The excitation follows the all-or-none principle. During physiological activation, type I fibers are recruited first, followed by type IIA fibers when additional force is needed and type IID fibers when the activation approaches the maximum.

Fatigue effects

Muscle fatigue occurs because the same motor units are stimulated repeatedly under stable stimulation parameters.[29,31] Fatigue can be decreased and endurance increased by using a well-designed stimulation protocol. There are 2 types of fatigue mentioned in the literature. First, the high-frequency fatigue occurs at ≥50Hz. It compromises the neuromuscular transmission by reducing the deactivation of neurotransmitters at the neuromuscular junctions, and muscle force subsequently decreases.[32] FES does not affect other processes known to cause fatigue (eg, excitation-contraction coupling).[33] Recovery occurs quickly by reducing the frequency.[29] Second, the low-frequency fatigue occurs in the range from 15 to 50Hz. The excitation-contraction coupling is reduced, and muscle force decreases. In this case, recovery is extended to hours or days.[33] However, repetitive stimulation of a muscle with a normative frequency can achieve better muscle fatigue resistance.[34] It has been observed in the quadriceps muscle that low-frequency stimulation can increase fatigue resistance.[35] Gorgey et al[29] have shown that only the frequency has an influence on fatigue and not the amplitude or the pulse width. In 7 healthy subjects who stimulated their quadriceps muscle, it was possible to reduce the fatigue from 76% to 39% by reducing the frequency of FES from 100 to 25Hz.[29] On a structural level, FES can cause a change in muscle fibers from type IID to type IIA and partly to type I.[36] That means that the altered fiber type composition can partly be reversed. Muscle fibers type I are more fatigue resistant. A muscle fiber shift from type I to type II occurs approximately 6 weeks after SCI.[37] Therefore, muscle fiber type conversion after FES can increase the fatigue resistance of stimulated muscles. Furthermore, the training can be performed more efficiently taking into account the torque-frequency relation. If the contractile speed of a chronically paralyzed muscle decreases, it should be possible to get the same muscle force by decreasing the frequency (Hz).[33]

List of abbreviations:

BR	**brachioradialis**
FES	**functional electrical stimulation**
LMN	**lower motor neuron**
SCI	**spinal cord injury**

Strength

The power output of muscles or muscle groups can be increased by FES after SCI.[2,38] Several studies in individuals with SCI have shown that it is possible to increase torque and power output by FES-supported exercises in the lower and upper extremities if the LMN is intact.[39,40] Furthermore, there is an increase in the physiological cross-sectional area of the stimulated muscles. Stimulation parameters must be chosen carefully to achieve the intended effect. The pulse width should be between 250 and 400μs. The frequency should be between 20 and 50Hz, and the amplitude should be as high as possible to stimulate as many motor units as possible.

FES and reconstructive arm and hand surgery

FES has a great potential to enhance hand surgery. It can be beneficial preoperatively because selective stimulation has a positive influence on the muscle structure, power output, cross-sectional area, and muscle fiber type adaptation. In postsurgical treatment, electromyography-triggered stimulation is applied with respect to retraining the transferred muscle to perform a new function and may affect neuroplastic changes that support motor learning. Additionally, strengthening of transferred muscles can be achieved.[41] Furthermore, preoperative FES testing of potential donor muscles is a simple and reliable method to determine if the contraction of the muscle is sufficient or if the muscle shows signs of denervation.

FES before surgery

Several issues must be addressed before a muscle can be selected as a donor to replace a lost function. First, it should develop sufficient force (M4 on British Medical Research Council Scale); second, it should have a sufficient physiological cross-sectional area. Similar criteria apply to the recipient muscles when they are considered for a nerve transfer.[42] After SCI, the muscle structure changes as a result of disuse or denervation.[33,37] The prerequisites for a recipient muscle are a certain number of contractible motor units and a sufficient cross-sectional area. The stimulation schedule of the donor muscle before surgery should contain low-frequency training to avoid muscle fatigue,[29] if possible in a loaded position or acting against gravity or resistance. The preparation of the recipient muscle should be similar but if possible performed using a functional movement (table 1). The training has to be carried out 3 times a week for at least 30 minutes during each session.[43] The training should start 12 weeks before surgery.[32,39] The best training is FES-supported arm cranking. An advantage of FES arm cranking is the synchronization of the movement (ie, stimulation and resistance of each muscle). However, preoperative training usually has to be done in a domestic setting; therefore, FES with a 2-channel stimulator in combination with physical therapy exercises in a loaded position or against resistance with portable weights could be used alternatively to FES-supported arm cranking.

FES after surgery

The recipient muscle has to be strengthened after the immobilization period. Training of the recipient muscle against resistance