A Perspective on the Control of FES-Supported Standing

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Abstract—This special section is about the control of electrical stimulators to restore standing functions to paraplegics. It addresses several important topics regarding the interactions of the intact central nervous systems (CNS) with the artificial control system. The topics are as follows: how paraplegics use their arms to help themselves stand up with functional electrical stimulation (FES); the user-driven artificial control of FES-supported standing up; a controller which is promising for the control of sitting down; the application of reinforcement machine learning for the controllers of standing up; arms-free standing with voluntary upper body balancing and artificially controlled ankle stiffness; and cognitive feedback in balancing. This Commentary introduces the papers in this section and relates them to earlier research.

Index Terms—Control, functional electrical stimulation (FES), paraplegia, rehabilitation, standing, standing up.

I. INTRODUCTION

INTEREST in the control of paraplegic standing, including standing up and sitting down, using functional electrical stimulation (FES) has increased in recent years. There may be several reasons for this. First, it clearly has great potential to provide both functional and therapeutic benefits. Functionally, it would allow paraplegics to reach further than when sitting in a wheel chair, make transactions at a counter, and communicate with other people at equal level; also it is a prerequisite for making transfers and stepping or walking. In complete paraplegic subjects, the functional benefit of standing may be larger than of gait, since, in the foreseeable future, travelling over more than short distances will still be easier in a wheel chair. At least as important as the functional benefits are the therapeutic benefits from loading the bones, extending the joints, improving the blood flow, and activating the muscles [30], [31].

A second reason for the renewed interest in standing is an appreciation of the central importance of the actions of the neurologically intact neuromuscular system of the upper body. While it may have been a platitude that paraplegics use their arms to help lift the body weight and balance when upright, the realization that the number of degrees of freedom of the paraplegic body are such that their posture may still

generally be controllable by the intact neuromuscular system [37] suggests that artificial controllers for standing by FES should be designed on this basis, and judged by the way they assist the user in the task. Two concurrent controllers are acting in parallel, the physiological system, which is under voluntary control, and the artificial support system (Fig. 1). This opens several interesting questions about the interaction of the artificial support system with the physiological system: how the user can be in continuous control of the standing task; what sensory feedback to provide to the user and to the artificial control system; and should the artificial controller try to minimize the upper-body effort or the fatigue in the stimulated muscles.

II. FES-SUPPORTED STANDING

FES-assisted standing and standing up in paraplegics was reported by Brindley *et al.* [5] and Bajd *et al.* [3], [4]. Since, it has been the topic of many studies, ranging from simulations in which the actions of the intact neuromuscular system have been neglected [16], [19], [15] to clinical trials of *ad hoc* controllers, for which there was no formal system identification of the plant [11], [26]. Stimulation without any feedback is still often used [17]. Kagaya *et al.* [18] propose to apply open-loop stimulation patterns for standing-up in paraplegics, which are based on the activation patterns measured on healthy subjects. Improvements have been suggested to allow muscles to rest so as to prolong endurance, for example by *posture switching* (e.g., Kralj *et al.* [20]) or using a hybrid orthosis [1], [35]. Veltink *et al.* [34] proposed to take account of the different functions of mono- and biarticular muscles in giving antigravity support and controlling body balance. Turk *et al.* [33] used biofeedback (i.e., feedback of sensor information to the intact neuromuscular system) to help with balance.

However, in other applications of FES, the actions of the intact neuromuscular system have been a command source, which the user may operate subconsciously. For example, in the upper limb, there is *extended physiological proprioception* [29], the “electronic bypass” [36], and indeed the *freehand* system [27]. For walking, Graupe *et al.* [12] used EMG to signal the action of the trunk in gait while intention detection has been used using mechanical signals [1], [35]. Kirtley and Andrews [21] used EPP with FES to control the knee angle when the foot was not touching the ground. However equivalent methods to integrate the artificial controller with the natural controller during standing tasks is relatively new [9].

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Fig. 1. In FES-supported mobility the physiological and artificial motor control systems operate in parallel, having several possible channels of interaction. Each system can be divided in a controller, a mechanical system ("plant") and a sensory system which supplies feedback to the controller. The neurologically intact central nervous system (CNS) is the controller of the physiological system. The artificial mechanical system describes orthoses, which may be used in combination with FES (hybrid system), but is not present when only using FES. The physiological and artificial motor systems can interact in many ways. 1) The intention of the user can be transferred to the artificial system by explicit user commands or implicit intention detection. Within the user defined objectives, the operation of the total system may be optimized according to physical criteria. 2) The artificial control system may interact with the CNS control by activating reflexes. 3) The artificial control system interacts with the body mechanics by the stimulation of muscles (FES). 4) The CNS may interact with the artificial control system by motor control signals derived from the neural system, for example, by electroneurography (ENG) or electromyography (EMG), thus transferring the intention of the user to the artificial control system in an implicit way. 5) The body and mechanical support system (orthosis) interact mechanically. 6) The artificial sensors sense the movement and interface forces of the human body. 7) Signals from physiological sensors can be derived by ENG. 8) The physiological sensory system of the user, which may be deprived of sensory information from the paralyzed parts of the body, may be supplemented by cognitive feedback of sensory signals derived from physiological sensors or obtained using artificial sensors.

III. PAPERS IN THIS SECTION

This special section of the IEEE TRANSACTIONS ON REHABILITATION ENGINEERING presents recent research in the area of FES-supported standing, including standing up and sitting down. The main theme is the interaction of the user's voluntary control with the artificial FES support system.

Work on *patient driven* control strategies for FES-supported standing-up is described by Riener and Fuhr [28] and Donaldson and Yu [10]. Donaldson and Yu are testing a control

method they proposed in an earlier paper [9], called control by handle reactions of leg muscle stimulation (CHRELMS), in which the stimulation of lower extremity muscles is constantly adapted in order to allow maximal unloading of the arms. The experiments reported here by Donaldson and Yu show the control actions of the arms, when paraplegics stand up with open-loop stimulation. These actions demonstrate a strategy which they call *quick kneelocking*. Riener and Fuhr [28] propose an alternative control method, which supports movements directed voluntarily by the user. They call this "Patient-Driven Motion Reinforcement" (PDMR). Their simulations indicate that both CHRELMS and PDMR can realize satisfactory standing-up, reducing arm forces in comparison with standing-up without FES. However, these results depend on an upper body model which may change when quick knee-locking is taken into account. The finding that both control methods yield similar joint trajectories to healthy subjects' may indicate that the methods are near optimal with respect to relevant physical criteria (e.g., minimal effort of both upper and lower extremities). It would be interesting to compare the performance of both CHRELMS and PDMR to a disturbance compensation controller which explicitly optimizes these criteria.

An important consideration is the requirement for sensors, because their number and positions may both limit practical application. CHRELMS requires a substantial set of sensors, measuring handle forces and joint positions relative to the application points of these handle forces. PDMR probably requires fewer sensors, since only the position and velocity of the body segments is needed. Suitably designed observers (e.g., [23]) may reduce the number of sensors and allow placement on acceptable positions on the body. It should be noted that important sensor developments have occurred in the last decade: small inertial sensors (accelerometers and gyroscopes) have become available which are suitable for prosthetic applications [2], [7], [22] and the feasibility of deriving sensory information from physiological sensors, for feedback in neural prostheses has been shown [13].

Dolan *et al.* [8] present preliminary experimental data on a bang-bang controller which uses a switching curve to turn quadriceps stimulation on and off. The primary purpose was to reduce the knee joint velocity near the end of the motion. Their results suggest that this controller may be more advantageous for sitting down than standing up. The absence of a reduction in the arm forces with closed loop control may be related to the fact that the hip was not actively extended by electrical stimulation [34].

The Riener-Fuhr controller (PDMR) is based on a detailed physiological model of the body and, in order to implement a controller for a real subject, many parameters would need to be identified. This may be difficult, and yet still not be very accurate, given the rapid changes in the muscles. It may be that the system identification problem can be avoided or diminished by utilising machine learning, which is the subject of a paper by Davoodi and Andrews [6]. They describe a self-adapting controller for FES-supported standing up and sitting down in the presence of upper body effort, which learns by *reinforcement*. The reinforcement learning method alters the behavior of a fuzzy control system. Their

simulations indicate that their method is able to self-optimize. An important question is whether their reinforcement method can learn sufficiently quickly to adapt to changing system characteristics, e.g., muscle fatigue. Experimental validation will show the eventual merit of the proposal.

Matjacic and Bajd [24] describe an exciting new method for arms-free standing with voluntary upper-body balancing, and with controlled ankle stiffness and biofeedback. They show that, if properly designed, the artificial control system can be very simple, though essential to enable the physiological control system to control unsupported standing. They also show the beneficial effect of cognitive auditory feedback in their experiments [25]. It should be noted that the system has been tested in a paraplegic subject with a fairly low lesion level (T12) who, therefore, has voluntary control of trunk muscles. In their experiments, the knees and hip joints were constrained by bracing. Perhaps, for higher level lesions, the balancing may be actively supported by stimulating the lower trunk muscles. Short-term arms-free standing may be relevant in daily life activities. However, functional standing also implies that objects can be moved with at least one hand [14], [32]. If this would introduce excessive disturbances for standing without arm support, the Matjacic and Bajd method may also assist balance while standing with one hand support.

Despite the exciting new approaches to FES-assisted standing discussed above, we should be aware that FES-assisted standing-up has not become a regular clinical method yet. Jaeger *et al.* [17] estimated that only 10% of all paraplegics are eligible for this therapy: those with a lesion between T4 and T12, good control over their upper extremities and no medical or other problems which would interfere with the application of FES for standing. However, eventually FES-supported standing may be beneficial to a larger population, patients with other neuromuscular disorders including incomplete paraplegics, hemiplegics, and those with multiple sclerosis or cerebral palsy.

For FES-supported standing to become clinical practice, we will have to demonstrate to our patients that because of our improvements to the systems, the functional and therapeutic benefits outweigh the disadvantages of risk, cost, poor reliability, and effort of use. To do so, it will not be sufficient just to further develop the methods presented in this special section, which should include making them easier to apply and fail-safe, but they must be taken from the laboratory to the clinic. We question whether the break-through can be reached with surface FES systems, as used in most of these investigations; implanted stimulators and sensors may be necessary.

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