Functional Electrical Stimulation for Postural Control

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***Abstract*— In this presentation, we will introduce two series of studies of our own, focusing on postural control using functional electrical stimulation (FES0. A simple linear controller can be applied to ankle joint control to stabilize standing posture. This method will be used for FES therapy for standing in near future. An open-loop controlled low-intensity FES can be applied to trunk muscles to stabilize sitting posture. This system can be used as an orthotics to stabilize sitting posture.**

I. Introduction

Functional electrical stimulation (FES) is a promising technology for regaining disabled motor function in individuals with neurological impairments, e.g., due to spinal cord injury (SCI) or stroke. Here, we introduce two series of studies of our own, focusing on postural control using FES. FES was initially developed as an orthotic tool, but is now frequently used as a therapeutic tool as well. The FES system for standing we are developing could be used for therapeutic use, and the one for sitting for orthotic use.

II. FES for Standing

A. Background

FES therapy (FET) promotes neuroplasticity and helps people with neurological impairments improve voluntary function. Growing evidence exists that regular use of FES therapy can result in recovery of functional abilities, especially in the upper limbs, after stimulation is discontinued. However, no study so far has examined the effect of applying FET to static postural control, e.g., during standing. We have set out to develop FES for standing, with a future aim of applying the solution as FET for balance recovery. FET for standing requires stimulating muscles responsible for maintaining balance at the appropriate time and with appropriate stimulation intensities. Hence, we have been investigating the physiological postural control system during standing to develop an FES system for standing that can provide appropriate stimulation to the relevant muscles.

Most of the early FES systems that facilitated standing were open-loop controlled [1], [2]. FET for standing, however, requires closed-loop control since human stance is controlled in a closed-loop manner. FES closed-loop control systems have been studied experimentally [5]-[11] and theoretically [12]-[14]. While not all are based on physiological control, we believe it to be advantageous for an FES system for standing to mimic the physiological control system.

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B. Physiological Control Strategy of Standing

We have been investigating the physiological control system of the ankle joint, which is the primary joint in controlling the location of the center of mass (COM) of the entire body. It is well known that the control strategy of the ankle joint can be modeled as a closed-loop proportional-derivative (PD) controller. In our own studies, we demonstrated that the control mechanism regulating the activity of the plantarflexors relies notably on the COM velocity information, and that such control mechanism can be approximated as a closed-loop proportional-derivative (PD) controller with a high derivative gain [15], [16].

In these initial studies, we considered only the active torque component as the output of the PD controller without considering the passive torque component. In the next step, we investigated a more detailed model of the physiological control system including ankle muscle dynamics (i.e., the torque generation process at the ankle muscles) and passive torque components [17], [18]. We found that the phase delay induced by the muscle dynamics is quite lengthy during quiet standing, which is a factor in destabilizing the physiological control system. To overcome this delay, the physiological control system requires (1) a high derivative gain, which is beneficial for predicting future COM displacements; and (2) a considerable contribution from passive torque components, which are not affected by such a delay. In fact, we have shown that about 70% of the required torque should be provided by passive torque components [17], [18].

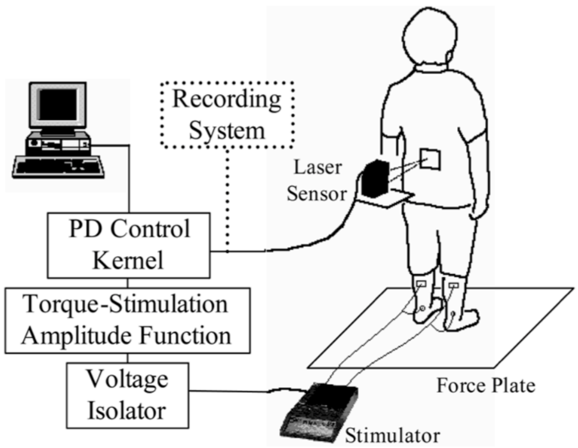

Fig. 1. Schematic of the FES ststem for standing. Laser measurements representing the fluctuation of spontaneous body sway were sent to the controller, which determined the level of active ankle torque that was needed to stabilize the system. Cited from [11].

C. FES for Standing

The simple PD controller identified in the previous studies can be used for designing effective FES systems. We have tested the feasibility of applying our findings [15], [16] by investigating the use of respective FES controllers in a single-participant pilot study (Fig. 1)[11]. We demonstrated that a PD-controlled FES system reduced a paralyzed individual's spontaneous postural sway during quiet standing as long as its derivative gain is sufficiently large (Fig. 2)[11]. However, the control gains used in this study were chosen quite arbitrarily and not identified following systematical investigations. Aiming to systematically investigate the physiological control system of standing and effectively develop an FES system that will stabilize the ankle joint during standing, we have developed a testing platform, the Inverted Pendulum Standing Apparatus (IPSA) [19], [20]. IPSA is a mechanical, human-sized inverted pendulum, whose angular position is determined by the participant's ankle joint angle as controlled by the FES system. As the participant is fixed in the IPSA frame, the participant's ankle muscles are relaxed (i.e., no volitional muscle contraction involved) [21], allowing performance testing of FES systems even with healthy participants (supported-standing paradigm). In [19], we systematically investigated the best gain set for a PD-controlled FES system and tested its performance using IPSA. We successfully demonstrated that the PD-controlled FES system stabilized the human-sized pendulum during quiet and perturbed standing for three able-bodied subjects.

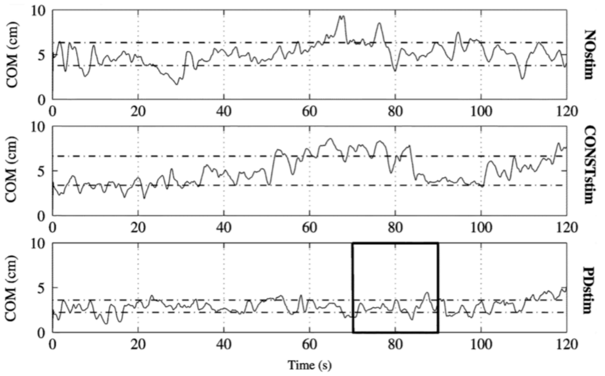

Fig. 2. Fluctuation of COM position during quiet stance. COM fluctuation without stimulation (NOstim), COM fluctuation with constant stimulation (CONSTstim), and COM fluctuation with controlled stimulation (PDstim). Dashed horizontal lines in each plot define the range of the mean±SD. The body sway in PDstim had a smaller magnitude than in NOstim and CONSTstim, indicating that the PD controller stabilized the body better than the others. Cited from [11].

III. FES FOR SITTING

A. Background

The inability to voluntarily control the trunk musculature and stabilize seated posture is a major problem for many individuals with SCI. Any injury to the spinal cord between the head and the tenth thoracic vertebra can cause some degree of trunk function impairment due to the loss or mutilation of respective sensorimotor information. Rapid and optimal improvement of trunk control is of high priority for affected individuals, outweighing their desire, for example, to walk again.

Various efforts have attempted to improve sitting stability of individuals with SCI, primarily by customizing wheelchair configurations. Recent studies suggest that FES may have the potential to facilitate or even restore trunk control during sitting and other functional tasks [22]. For example, FES has been used in open-loop control schemes to activate the paralyzed trunk musculature during sitting to increase seated postural stability [23], [24], facilitate bimanual tasks that individuals with SCI are otherwise unable to complete [23], [25], and increase the user's control with respect to wheelchair propulsion speed [26]. Besides these experimental approaches, also model-based studies have been performed for the purpose of identifying adequate closed-loop control strategies [27], [28] and the necessary torque levels for facilitating trunk stability via FES [28], [29].

All of these efforts offer valuable insights into the feasibility and effectiveness of FES for enhancing or restoring trunk stability in individuals with SCI. At the same time, larger FES activation levels that can stabilize the upper body against external perturbations have been shown to lead to muscle fatigue [24]-[27], compromising the functional abilities and safety of the user. Another method of using FES technology is to apply low-intensity FES with the goal of increasing trunk stiffness and damping. Weak muscular co-contractions during voluntary sitting have been shown to significantly increase trunk stiffness and contribute to postural control in seated healthy individuals. Increasing trunk stiffness via low-intensity FES may, however, not only enhance postural stability in any horizontal direction, but also mitigate muscle fatigue as one of the largest challenges associated with FES solutions. Based on these considerations, we hypothesize a positive effect of low-intensity FES on multidirectional trunk stiffness during sitting.

In the following two studies, we investigated the effect of low-intensity FES of a few selected trunk flexors and extensors on (1) trunk stiffness; and (2) postural sway.

B. Increasing Trunk Stiffness via FES

In [30], we investigated how multidirectional trunk stiffness changes in response to low-intensity FES of a few selected trunk flexors and extensors. Fifteen able-bodied participants sitting naturally were randomly perturbed in eight horizontal directions. Trunk stiffness and damping during natural and FES-supported sitting conditions were quantified using force and trunk kinematics in combination with two models of a mass-spring-damper system. Our results indicate that low-intensity FES can increase trunk stiffness in healthy individuals, and this specifically for directions associated with the stimulated muscles. In contrast, trunk damping was not found to be altered during FES. The obtained findings suggest that low-intensity FES is a simple and effective method for increasing trunk stiffness on demand.

C. Improving Postural Stability of Sitting via FES

In [31], we investigated the effect of low-intensity FES on the center of pressure (COP) fluctuations during natural and FES-supported quiet sitting. Fifteen able-bodied individuals participated in this study. Each participant sat on an instrumented chair and maintained a quiet sitting posture for 30 seconds. The COP fluctuation on the seating surface was calculated to compare sitting stability of participants during natural and FES-supported quiet sitting. The results showed that (1) the COP's mean velocity, mean frequency and power frequency were higher during FES-supported sitting; (2) the frequency dispersion for anterior-posterior fluctuations was smaller during FES-supported sitting; and (3) the mean distance, range and centroidal frequency did not change during FES-supported sitting. An additional simulation study showed that increasing trunk stiffness had the same effects on COP fluctuations as the FES. The results of this study suggest that low-intensity FES applied to key trunk muscles increases the speed of the COP fluctuations by increasing the trunk stiffness during quiet sitting.

IV. Conclusion

We demonstrated that a closed-loop controlled FES system applied to the ankle muscles can stabilize quiet stance. Further, our results indicate that open-loop controlled, low-intensity FES applied to superficial trunk muscles can increase trunk stiffness and stabilize upright posture during quiet sitting.

We believe that the former can be used for FET for standing, which could assist individuals with neurological impairments in improving their standing balance. The latter could be used as an orthotics to stabilize affected individuals' sitting posture during activities of daily living.

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