1.5 Controlling of the Functional Electrical Stimulation–Enabled Human Upper Extremity

The development of Functional Electrical Stimulation (FES) systems that can bring back essential useful upper-extremity movements demands controllers that can achieve accurate and consistent performance over many dynamically-varying conditions. This following section will review the current status of FES control technology for upper-extremity systems and discuss further technological advancements in FES control technology necessary to achieve more natural upper-extremity movements in individuals with high-level spinal cord injuries.

The Upper-Extremity Functional Electrical Stimulation Control Problem

Controllers for Functional Electrical Stimulation (FES) systems are most often structurally complex in structure, because they must solve the sensorimotor coordination problems normally handled by the central nervous system (Davoodi et al. 2007). These controllers select the nerves or muscles to be stimulated and apply, with a particular amount quantity of current and, in a particular, specific sequence, to do perform the desired movement.

For upper-extremity movements, postural stability must be maintained as the hand travels to its target location (Crago et al. 1996). Since reaching tasks are goal-directed, FES controllers must allow a wide variety of actions, each requiring a unique stimulation pattern, since reaching tasks are goal-directed. In contrast,
with lower-extremity FES systems to that restore walking or sit-to-stand movements that can utilize cyclic or predictable stimulation patterns to produce stereotyped movements.

The physiological properties of FES systems are related to a challenging control problem. The muscles being stimulated are nonlinear and time-varying actuators. Moreover, muscle response will vary non-linearly with fatigue (Lynch and Popovic 2005; Popadic Gacesa et al. 2010). When stimulation is applied, muscles can become stronger and resistant to fatigue; this training effect should be taken into account (Lynch and Popovic 2005). In individuals with incomplete spinal cord injuries, some muscular function may be retained and should be incorporated into the controller. Muscle functions can be redundant; thus, making the selection of specific muscles necessary must be selected for a given task.

FES systems have an inherent delay between the time of stimulation and the start of muscle contraction; and Additionally, there are also delays related to signal processing and transmission are also present within the electrical stimulation system (Lynch and Popovic 2005; Cooman and Kirsch 2012). Muscular spasticity may be present, which resulting in increased muscle tone and unpredictable muscle activity (Rekand et al. 2012; Skold et al. 1999). Methods for objectively assessing spasticity are unsystematic (Priebe et al. 1996).

Additional challenges arise because joints are kinematically redundant and multiple-joint systems are inherently nonlinear (Lan et al. 1990). Moreover, joints can be coupled by multiarticular muscles (Adamczyk and Crago 2000). Further, joint contractures are often

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present (Diong et al. 2012) and can greatly limit the available range of motion that is available (Harvey et al. 2011).

Additionally, for upper extremity control must counter the effects of gravity makes it difficult to utilize move the arm. To address this, the arm, which is often supported by a mobile arm support that This support is intended to approximate a zero-gravity environment, however, but this support rarely achieves precise counteracting of gravity. And Moreover, external perturbations, such as interactions with objects, must be managed. We will refer to the grouping of these considerations when during the development of upper-extremity FES controllers collectively as the Upper-Extremity FES Control Problem.

Control Strategies for Upper-Extremity Functional Electrical Stimulation Systems

Feedforward (i.e., open-loop) control, which is also referred to as open-loop control, involves the calculation and application of muscle stimulation patterns for to generating movement in a pre-defined way manner. For example, stimulation of the triceps muscle might be pre-programmed to create elbow extension (Crago et al. 1998). Feedforward stimulation sequences can be applied volitionally by the user, or can be programmed to execute in sequence, such as when locomotion is restored (Kostov et al. 1995). No feedback signals are used in feedforward open-loop control, which makes making it useful for performing rapid movements (Crago et al. 1996). If it is necessary, controller parameters can be tuned between uses, but feedforward control does not allow dynamic adjustment of controller parameters. This feature prevents feedforward
controllers from adjusting to changes in the system, such as muscle fatigue or a mass held in the hand.

In order for the feedforward controller to succeed, the arm system being controlled must closely match the modeled or estimated system for which the controller has been tuned for; if the model does not match the actual system, bad performance will result. Thus far, feedforward control has dominated the clinical applications of FES systems (Popovic et al. 2001; Lynch and Popovic 2008; Peckham and Knutson 2005) due to its simplicity of implementation. Because no sensors are required, feedforward control systems are easy to put on and take off, and this can be a significant consideration (Braz et al. 2007; Lynch and Popovic 2008; Braz et al. 2009). Clinical applications of feedforward control for upper-extremity FES systems have included hand grasping (Kilgore et al. 1997; Mauritz and Peckham 1987; Keith et al. 1989) and elbow extension (Crago et al. 1998).

Feedback (or closed-loop) control addresses some of the shortcomings of feedforward control (Abbas and Triolo 1997; Crago et al. 1996). Because feedback control utilizes sensors, it is possible to identify inaccuracies in arm control and to correct the arm’s position if it differs from the desired position. Such error correction enables feedback control to adjust to dynamic changes such as muscle fatigue. However, an error signal must be generated in order to produce controller action, and since feedback control inherently involves a delay, this makes feedback control preferable for use in slow and posture-maintaining movements rather than fast movements (Crago et al. 1996).
Although feedback control is more accurate than feedforward control, it is also considerably more challenging to implement because it requires sensors mounted on the body (Lan et al. 1998). Putting on and taking off the sensors for each use is time-consuming, and calibrating the sensors consistently between uses involves a challenge (Braz et al. 2007; Braz et al. 2009). Notably, more than one sensor is required to achieve the accuracy necessary for adequate control (Kirkwood et al. 1989; Tong and Granat 1999; Andrews et al. 1995).

Additionally, there are properties of physiological systems that pose problems for FES feedback control. Muscles respond quite slowly to stimulation (Solomonow 1986; Abbas and Triolo 1997) and have time-varying and nonlinear properties when stimulated (Lynch and Popovic 2008; Leonas 1986). Thus, there are systemic delays in response within FES systems that may cause problems for fast movements (Crago et al. 1996; Stroeve 1996). For these and other reasons, the clinical utilization of feedback control has been limited (Crago et al. 1996; Peckham and Knutson 2005).

References

