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

> **Commented [CP1]:** Here and throughout, I have recommended spelling out all abbreviations used in headings, as is typically recommended in scientific writing.

The development of f~~F~~unctional ~~E~~electrical ~~S~~stimulation (FES) systems that can ~~bring back~~restore essential ~~useful~~ upper-extremity movements demands controllers that can achieve accurate and consistent performance over ~~many~~ dynamically~~-~~ varying conditions. ~~The~~ 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~~required to achieve more natural upper-extremity movements in individuals with high-level spinal cord injuries.

> **Commented [CP2]:** I added "FES" here. In general, acronyms should be introduced into the text when the expanded form is first used. After introducing an acronym with its expanded form one time, only the acronym form of the word needs to be used.

The Upper-Extremity Functional Electrical Stimulation Control Problem

Controllers for ~~Functional Electrical Stimulation (~~FES~~)~~ systems are ~~most~~ often structurally complex ~~in structure,~~ because they ~~have to~~must ~~solve~~ address ~~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 ~~a~~ the desired movement. For upper-extremity movements, postural stability ~~needs to~~must be maintained ~~as~~ while the hand travels to its target location (Crago et al. 1996). ~~Since~~As reaching tasks are goal-directed, FES controllers ~~to~~ that restore movement~~s~~ must allow a wide variety of actions, each ~~necessitating~~ requiring a unique stimulation pattern~~, since reaching tasks are goal-directed~~. In ~~This~~ contrast,~~s~~

> **Commented [CP3]:** As mentioned earlier, once an acronym has been introduced into the text with its expanded form, only the acronym form of the word needs to be used. I have applied this throughout the remainder of the text as needed.

~~with~~ lower-extremity FES systems ~~to~~ that restore walking or sit-to-stand movements ~~that~~ can utilizse 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~~ variesy nonlinearly 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.

Commented [CP4]: I would recommend being more specific here, if possible. For example, do the physiological properties of FES systems create a challenging control problem, or do they have to solve or address a challenging control problem?

Commented [CP5]: This phrase isn't incorrect, but "considered" would be a good alternative and more concise.

I would also recommend adding more information here. For example, should this training effect be taken out when FES systems are developed?

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 with~~in the electrical stimulation system (Lynch and Popovic 2005; Cooman and Kirsch 2012). Muscular spasticity may be present, ~~which~~ resultings 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).

Commented [CP6]: In the citation earlier in this paragraph, the citations are listed in chronological order, and here they are listed in alphabetical order according to the first author's surname. Please check which format the journal to which you are submitting prefers and edit the citations here and throughout as they recommend.

Commented [CP7]: If this is referring to current methods (i.e., if future methods may be systematic), I would recommend changing this to "Current methods."

Additional challenges arise because jJoints are kinematically redundant and multiple-joint systems are inherently nonlinear (Lan et al. 1990). Moreover, jJoints can be coupled by multiarticular muscles (Adamczyk and Crago 2000). Further, jJoint contractures are often present (Diong et al. 2012) and can greatly limit the available range of motion that is available (Harvey et al. 2011).

Additionally, for in upperUpper-extremity control must counter the effects of, gravity makes it difficult to ustilizsemove 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, buthis supportt rarely achieves precise counteracting of gravity. AndMoreover, external perturbations, such as interactions with objects, must be managed. We will refer to the grouping of these considerations when during the development ofing 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 generateing movement in a pre-defined waymanner. 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 makesmaking 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 n’ot 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 f~~F~~or~~The feedforward controller is tuned for a specific ~~to succeed, the arm system being controlled must closely match the~~ modeled or estimated system ~~that for which the controller has been tuned for~~; if the model does n'ot match the actual system, ~~bad~~ performance will ~~result~~ be poor (Crago et al. 1996). Thus~~So~~ 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~~ simple ~~of~~ implementation. ~~Because~~ As no sensors are required, feedforward control systems are easy to put on and take off, ~~and this can be~~which is 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~~ i.e., closed-loop) control ~~takes care of~~addresses some of the shortcomings of feedforward control (Abbas and Triolo 1997; Crago et al. 1996). ~~Because f~~Feedback control utilizses sensors, ~~it i's possible to identify~~allowing the identification of inaccuracies in arm control and ~~to~~ the correction of the arm's position if it differs from ~~a specified~~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~~Due to its ~~feedback control~~ inherent~~ly~~ ~~involves a~~ delay, ~~this makes it~~feedback control is preferable ~~to~~ for use ~~it for~~in slow and posture-maintaining movements rather than fast movements (Crago et al. 1996).

Commented [CP8]: It is unnecessary to restate that you are discussing the "arm system" here since you have primarily been focusing on this in the earlier part of the manuscript.

Commented [CP9]: I would recommend being a bit more specific here, if possible. For example, does this mean that the simplicity of use is a significant consideration when choosing which type of FES system to use?

Although feedback control is more accurate than feedforward control, it is ~~also much~~considerably more challenging to implement because it ~~needs~~ requires sensors mounted on the body (Lan et al. 1998). ~~Putting on~~Applying and ~~taking off~~removing the sensors ~~for each use~~ is time-~~-~~consuming, and calibrating the sensors consistently between uses i~~nvolve~~s a challenge (Braz et al. 2007; Braz et al. 2009). Notably, m~~M~~ore 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~~The properties of physiological systems ~~that pose problems~~present challenges 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 manifest systemic delays in responses that may ~~cause problems~~be problematic for fast movements (Crago et al. 1996; Stroeve 1996). For these ~~many~~ reasons, the clinical use~~tilizsation~~ of feedback control has been limited (Crago et al. 1996; Peckham and Knutson 2005).

References

Adamczyk MM, Crago PE. 2000. Simulated F~~f~~eedforward ~~n~~Neural N~~n~~etwork C~~c~~oordination of ~~h~~Hand ~~g~~Grasp and ~~w~~Wrist ~~a~~Angle in a N~~n~~europrosthesis. *IEEE transactions on rehabilitation engineering*. 8(3): 297–304.

Commented [CP10]: If there are other reasons that are not included here, I would recommend changing this to “For these and other reasons.”

Commented [CP11]: Since all the journals were written in sentence case (only the first letter capitalized), I did not make any changes to the journal titles. However, please check the guidelines for the journal to which you are submitting this manuscript to determine which format they prefer for journal titles and update the titles throughout, if necessary (for example, “*IEEE Transactions on Rehabilitation Engineering*”).

Crago PE, Lan N, Veltink PH, Abbas JJ, Kantor C. 1996. New Control Strategies for Neuroprosthetic Systems. *Journal of rehabilitation research and development*. 33(2): 158–72.

Davoodi R, Urata C, Hauschild M, Khachani M, Loeb GE. 2007. Model-Based Development of Neural Prostheses for Movement. *IEEE transactions on biomedical engineering*. ~~Volume~~ 54(~~,~~ ~~Issue~~ 11): 1909–18.

Popadic G~~acesa~~ J, Ivancevic T, Ivancevic N, Popic P~~aljic~~ F, Grujic N. 2010. Non-Linear Dynamics in Muscle Fatigue and Strength Model during Maximal Self-Perceived Elbow Extensors Training. *Journal of biomechanics*. 43: 2440–3.