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Adaptive Control with Concave/Convex Parameterization for an Electrically Stimulated Human Limb

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Abstract: In this paper, we propose a new adaptive controller for the lower leg limb motion tracking problem that is inherent to neuromuscular electrical stimulation systems. The control accounts for uncertainties in the system parameters by exploiting the concavity and convexity of the model functions. The resulting control law is continuous and guarantees practical tracking for the limb angular position and velocity. The control performance is demonstrated via a simulation.

Keywords: Neuromuscular electrical stimulation, musculoskeletal model, adaptive control, nonlinear parameterization.

1. INTRODUCTION

Neuromuscular electrical stimulation (NMES) refers to the technology where skeletal muscles are externally stimulated in order to restore functionality to human limbs with motor neuron disorders [32]. This is accomplished via skin or implanted electrodes which upon voltage excitation produce muscle contraction and consequently joint torque and limb motion. NMES is an active area of investigation in the biomedical and rehabilitation engineering research communities since it is a key technology for realizing neuroprosthetic devices.

Control of NMES systems is a challenging problem because the muscle dynamics are nonlinear and highly uncertain. Common approaches for generating desired limb motion are open-loop control [7, 12] and traditional feedback control (e.g., PID control). These approaches however either fail to guarantee closed-loop stability or produce unsatisfactory results [15, 30]. An early review of NMES control methods can be found in [2]. The application of advanced feedback control methods is now possible due in part to numerous studies devoted to understanding and modeling the nonlinear physiological and mechanical dynamics of muscle stimulation, activation, and contraction. One of the first modeling results was Hill's work in the 1930's [13]. Since then, the identification and modeling of muscle dynamics has received considerable attention from various research groups; see, for example, [4,6,7,9,11,17,21,28,31]. Advanced NMES control techniques include sliding mode control [15], adaptive control [19, 36], neural network control [10, 29, 33, 35], dynamic robust control [34], time-delay compensation [16, 32], and switching control [5].

The NMES mechanical dynamics contains uncertain parameters that appear nonlinearly in the elastic and damping terms, i.e., it is a *nonlinearly parametrized* system. This characteristic creates obstacles for the design of adaptive controllers since classical adaptive schemes are based on the unknown parameters appearing linearly in the model. As a result, most advanced NMES controllers that compensate for modeling uncertainties compensate for *functional* uncertainties; e.g., the neural network controllers in [10, 29, 33, 35] and the robust-like controllers in [15, 32]. One can argue that if the uncertainties are only parametric in nature, then such controllers are an "overkill". (Note that the adaptive controller in [19] assumes the NMES mechanical parameters appear linearly.)

The design of adaptive controllers for nonlinearly parametrized systems is a nontrivial task. Since the mid 1990's, some researchers have labored in this area and devised many interesting results. For example, [26] proposed an adaptation scheme for stabilization of systems with concave parameterizations. In [1], a min-max adaptive controller was designed for first-order nonlinear systems with concave/convex parameterizations which ensures racking with prescribed precision. This result was extended in [18] to second-order nonlinear systems with extended matching. The concave/convex parameterization assumption of [1, 18] was removed in [22] to allow all nonlinear parameterizations where the parameters lie in a known compact and appear through additive, continuous, scalar, nonlinear functions. In [24], it was shown how to convexify nonlinear parameterizations to enable the use of adaptive controllers for convexly parameterized nonlinear systems. The work in [8] proposed a semi-adaptive stabilization control law for convexly parameterized systems that switches between adaptive and robust controllers. In [25], an adaptive control for multilinearly parameterized systems was introduced that combines convex and concave reparameterizations to ensure stability. A simple, adaptive stabilization controller with a linear-in-parameter-like structure was designed in [14] for systems satisfying the extended matching condition with Lipschitzian parameterizations.

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To the best of our knowledge, the only adaptive control to directly account for the nonlinearly-parameterized dynamics of the human shank-knee joint was recently proposed in [36]. Specifically, the design exploited the Lipschitzian parameterization of the system model by applying the result in [14] to compensate for parametric uncertainties. The resulting, torque-level control input is discontinuous and ensures asymptotic tracking for the angular position and velocity of the lower limb movement.

In this paper, we propose an alternative solution to the adaptive tracking control problem for the nonlinearly parametrized limb dynamics. Here, we take explicit advantage of the concavity or convexity of the model functions with respect to the nonlinear parameters. The foundation for our design is the adaptive strategy introduced in [1, 18]; however, we introduce a few modifications to simplify the resulting control algorithm. Since our mechanics dynamics are of order two, we first employ a filtered tracking error [3] to convert it into a first-order system. We also bypass the min-max optimization procedure since our main control objective is closed-loop stability. Finally, we utilize a simple projection algorithm on some of the parameter estimates which facilitates the Lyapunov stability analysis and control implementation. Our adaptive control is continuous and shown to ensure practical tracking for the angular position/velocity of the limb. A verification of the control performance is provided in the form of a computer simulation.

2. PRELIMINARIES

We provide the definition of convex/concave functions along with a related Lemma.

Definition 1. A C^1 function $f(\lambda) : \mathbb{R} \to \mathbb{R}$ is said to be *convex* on $\Theta = [\lambda_{\min}, \lambda_{\max}]$ if

$$f(\mu\lambda_1 + (1-\mu)\lambda_2) \leq \mu f(\lambda_1) + (1-\mu) f(\lambda_2), \quad (1)$$

and *concave* if

$$f(\mu\lambda_1 + (1-\mu)\lambda_2) \geq \mu f(\lambda_1) + (1-\mu) f(\lambda_2), \quad (2)$$

$\forall \lambda_1, \lambda_2 \in \Theta$ and $\forall \mu \in [0, 1]$.

Lemma 1. For any C^1 function $f(\lambda) : \mathbb{R} \to \mathbb{R}$ that is convex on $\Theta = [\lambda_{\min}, \lambda_{\max}]$: [1]

$$f'(\lambda_{\min}) \leq f'(\lambda) \leq f'(\lambda_{\max}), \ \forall \lambda \in \Theta \quad (3)$$

where $f' = df/d\lambda$. If the function is concave, then

$$f'(\lambda_{\min}) \geq f'(\lambda) \geq f'(\lambda_{\max}), \ \forall \lambda \in \Theta. \quad (4)$$

3. MODEL

We consider the musculoskeletal model for a human using the leg extension machine from [7, 9, 32]:

$$J\ddot{q} + B(\dot{q}) + K(q) + G(q) = u \quad (5)$$

where $q(t) \in \mathbb{R}$ is the angular position of the lower leg limb about the knee joint,

$$B(\dot{q}) = b_1\dot{q} + b_2 \tanh(b_3\dot{q}) \quad (6)$$

is the damping moment,

$$K(q) = k_1 \exp(-k_2 q)\, q - k_3 \exp(-k_4 q) \quad (7)$$

is the elastic moment,

$$G(q) = mgl \sin(q) \quad (8)$$

[1] The proof of Lemma 1 is omitted since the results can be easily verified by graphical means.

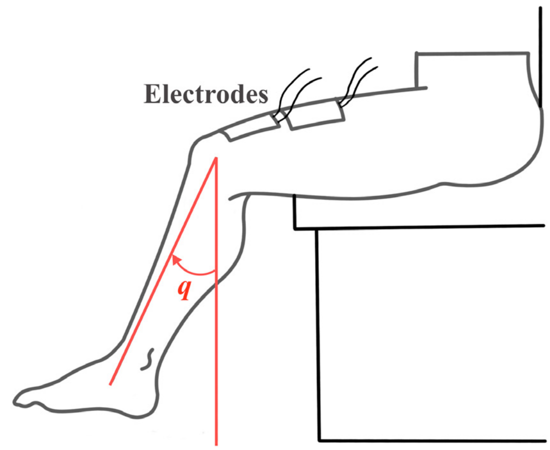

Fig. 1. Depiction of the lower limb with electrode stimulation of the quadriceps muscle.

is the gravitational moment, $u \in \mathbb{R}$ is the torque-level control input generated by electrode stimulation of the quadriceps muscles, the constant parameters J and m represent the constant inertia and mass of the lower limb/machine combination, respectively, and l is the distance between the knee joint and center of the mass of the lower limb/machine. The parameters b_i and k_i in (6) and (7) are positive and constant. As shown in Figure 1, the leg extension machine in [7, 9, 32] was designed with the user in sitting position such that the vertical position for the free-swinging lower limb is $q = 0$, and $q > 0$ when the knee joint extends. Note that the human knee joint is physically limited by $|q| \leq \pi/2$. Also, notice that $K(q)$ does not vanish at $q = 0$ because of the existence of a non-zero, resting knee angle [7].

4. CONTROL OBJECTIVE

The control objective is to design an adaptive law $u = u(q, \dot{q}, t)$ to asymptotically track any bounded C^2 reference trajectory $q_d(t)$ satisfying $\sup|q_d(t)| < \pi/2$ [2] and $(\dot{q}_d(t), \ddot{q}_d(t)) \in \mathcal{L}_\infty$ with the constraint that *all* parameters in (5)-(8) are unknown. We make the following assumptions about the unknown parameters of (5)-(8):

- The parameters that appear nonlinearly in the model, i.e., k_2, k_4, and b_3, lie in a known compact set. That is, parameter $\bullet \in [\bullet_{\min}, \bullet_{\max}]$ where $\bullet_{\min}$ and $\bullet_{\max}$ are known positive constants.
- The upper bound on the parameters k_1, k_3, and b_2 are known and denoted by $\bullet_{\max}$.

Our tracking objective is quantified by the tracking error

$$e = q - q_d. \quad (9)$$

To facilitate the control design, we also introduce the filtered tracking error [3]

$$r = \dot{e} + \mu e, \quad (10)$$

where $\mu > 0$ is a user-defined control gain, and the following tuning error [1]

$$r_\epsilon = r - \epsilon S(\frac{r}{\epsilon}), \quad (11)$$

[2] This condition stems from the fact that the knee joint angle cannot go beyond $\pm\pi/2$.