UNIQUE SOLUTION FOR FEED-FORWARD CONTROL OF NEUROPROSTHETIC SYSTEMS CHARACTERIZED BY REDUNDANT MUSCLES ACTING ON MULTIPLE DEGREES OF FREEDOM

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INTRODUCTION

We previously developed a method for implementing feedforward neuroprosthetic controllers for musculoskeletal systems with multiple degrees of freedom and complex mechanical interactions [1]. These controllers employed inverse models of the musculoskeletal systems under control. Experimental tests showed poorer performance than expected, which we attribute to redundancy of the data used to develop the inverses. The inverse relationship between muscle output and electrical stimulation is not unique (most joints have redundant actuation with non-stationary input-output muscle properties and coupled degrees of freedom) and if left unrestricted, neural networks trained to model the inverse may produce undesirable solutions. To overcome this problem, we automated a method to choose a single optimal inverse prior to network training [2]. Our present work involves obtaining this unique inverse solution and training a controller capable of independently controlling coupled degrees of freedom. We evaluate our solution method by testing the controllers in simulation and experimentally with able-bodied and spinal cord injured human subjects.

METHODS

For simulation studies, we developed a forward model of static isometric force production at the tip of the thumb, controlled by four extrinsic and intrinsic muscles. This model, which parallels our experimental model, allows us to generate time-varying forces in three directions. Muscle activation is modeled as a nonlinear function of the electrical stimulus. The model includes random noise and a linearly-decreasing fatigue factor that scales the maximum muscle force with every muscle contraction.

Our general approach (Figure 1) is to first create a system model of the time-varying input-output data with a time-invariant artificial neural-network. The system model smoothes the output muscle forces at the tip of the thumb, eliminating their time-variance. The system model also allows us to increase the amount of time-invariant input-output data by means of its interpolation capabilities. We choose unique input-output patterns from this time-invariant data that optimize specific performance criteria, such as minimum co-activation, which allows us to eliminate redundancy and thus obtain a unique solution. We train an inverse-model, static, feedforward, artificial neural network controller (Figure 2) with these optimal input-output data.

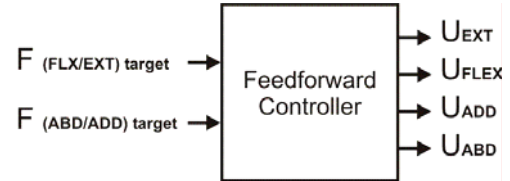Figure 1: Process for obtaining a unique solution.

Figure 2: Feedforward controller. The inputs are the target flexion/extension and abduction/adduction forces at the thumb tip. The outputs are the stimulus required for the extensor, flexor, adductor and abductor muscles.

We first study redundancy by stimulating only a pair of antagonists (extensor pollicis longus and abductor pollicis brevis) controlling flexion/extension of the thumb's carpometacarpal joint. We then incorporate coupling to the system by stimulating two additional muscles (flexor pollicis longus and adductor pollicis) allowing us to control abduction/adduction as well.

RESULTS AND DISCUSSION

We demonstrated the feasibility of this approach with a simplified model of a pair of antagonist muscles controlling a single degree of freedom [2]. The system model eliminated redundancy due to noise, and the optimization produced training data that eliminated mechanical redundancy by optimizing co-contraction. We expect similar results with the more realistic simulation model we are implementing currently, which will be followed by experimental tests. The methodology is general enough that it will be suitable for a wide variety of musculoskeletal systems. The use of neural networks for the controller allows us to improve generalization of muscle stimulation. Furthermore, by allowing independent control of redundant systems with coupled degrees of freedom, the function restored by neuroprostheses can be improved.

REFERENCES

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