Building Fatigue Resistance into Upper Limb Neuromuscular Stimulation Control Schemes

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218.08

Introduction

Our research focuses on improving current FES control methods by incorporating clinically-feasible limb stiffness modulation

Novelty

Here, we expand our previous work[1] using the Dynamic Arm Simulator[2] to provide an improved method for calculating one's unique FES control parameters

- Accounts for redundant and biarticular muscles
- Analytically determines muscle activations for balancing flexion/extension torques at various positions *and stiffness levels*
- Can reduce errors due to fatigue by adjusting the balance of stimulation across redundant muscles to account for muscles with different rates of fatigue
- Process is adaptable to when single electrode channels activate multiple muscles such as with nerve cuff electrodes

1. T Johnson and D Taylor 2021 *J. Neural Eng*.
2. EK Chadwick et al. 2009 *IEEE Trans Biomed Eng*.

Methods

This 'lookup table' method is an extension of the one used in the first demonstration of a BCI-controlled arm and hand FES system in an individual paralyzed from C4-level spinal cord injury[3]

1. Find passive torques P_i across the workspace

Hold the arm stationary at different locations throughout the workspace and measure passive torques on each joint

2. Find active torque A_{max} across the workspace

Measure active torques produced by applying increasing levels of stimulation to each muscle (or electrode) individually and record the *additional* torques needed to keep the arm stationary in each position. Record torques at maximum stimulation

3. Solve for torques that achieve desired position and stiffness

(a) Build a system of equations using P_i to fill the $\boldsymbol{x}$ vector and maximum active torque values to fill the $\boldsymbol{A}$ matrix.

(b) Solve the system of equations using *lsqminnorm()* to get the least squares minimum norm solution while limiting the scaling coefficients in the $\boldsymbol{c}$ vector to between 0 and 1.

Define relationship between desired stiffness *S* and torque

$$S = P_f + \sum_{i=1}^{N\ flexors} A_{f_i} - \left(P_e + \sum_{i=1}^{N\ extensors} A_{e_i}\right)$$

Substitute in scaling coefficient '*C*'

$$A_i = C_i \times A_{max}$$

Solve for *C*

$$\begin{array}{ccccccccccc} \text{x} & = & & & & \text{A} & & & \times & \text{c} \\ & & \text{Elbow flexor} & \text{Elbow extensor} & \text{Shoulder flexor} & \text{Shoulder extensor} & \text{Elbow \& Shoulder flexor} & \text{Elbow \& Shoulder extensor} & & \\ \begin{bmatrix} S\text{-}Pf_{elb} \\ -S\text{-}Pe_{elb} \\ S\text{-}Pf_{sho} \\ -S\text{-}Pe_{sho} \end{bmatrix} & = & \multicolumn{6}{c}{\begin{bmatrix} Mus_1 & 0 & 0 & 0 & Mus_5 & 0 \\ 0 & Mus_2 & 0 & 0 & 0 & Mus_6 \\ 0 & 0 & Mus_3 & 0 & Mus_5 & 0 \\ 0 & 0 & 0 & Mus_4 & 0 & Mus_6 \end{bmatrix}} & & \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{bmatrix} \end{array}$$

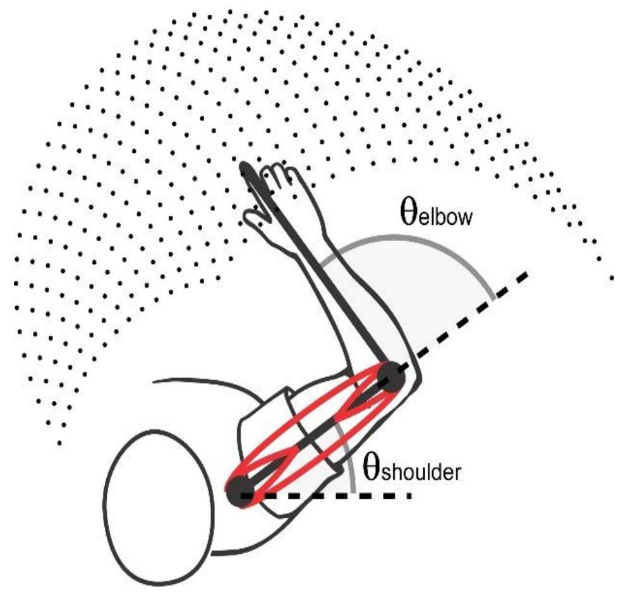
4. Generate initial lookup table

Scale max active torques by $\boldsymbol{c}$ to get the torque needed to achieve each desired arm configuration and stiffness. Use the stimulation-to-active-torque relationship (from step 2) to define the stimulation parameters that will give the proportion of the max active torque defined by $\boldsymbol{c}$.

5. Test initial lookup table and build final lookup table

(a) Apply the recommended stimulation values and record where the arm *actually* goes.

(b) Build the final lookup table using the actual arm positions collected in step 4 and interpolation to fill in intermediate values as needed (see 218.06).



Modifying Lookup Table for Fatigue

Define each muscle's fatigue rate r_{fatigue} :

$$\frac{\%\ A_{max}\ lost}{\text{second}}$$

Scale A_{max} based on the *anticipated* reduction in torque due to fatigue

Re-compute *C* in step 3 and similarly scale to A_{max}; build lookup table according to steps 4-5

3. AB Ajiboye et al. 2017 *The Lancet*

Lookup Table Performance for Fatiguing Muscles

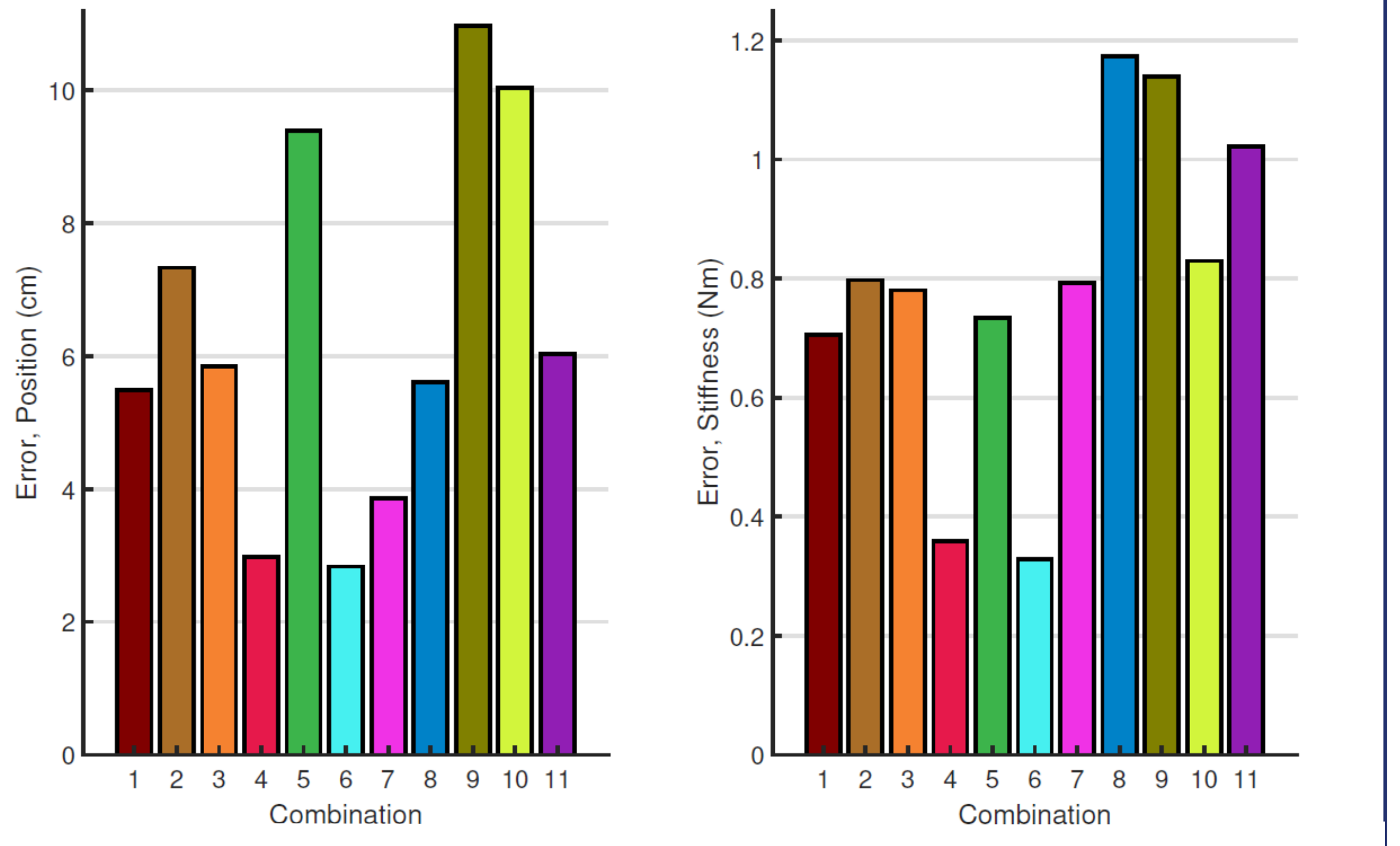
As a proof-of-principle, 11 conditions were tested with one (1-6) or two (7-11) of the six muscles fatigued with r_{fatigue} = 0.05% per second

	1	2	3	4	5	6	7	8	9	10	11
Shoulder flexor	X						X		X		
Shoulder extensor		X						X		X	
Elbow flexor			X					X	X		
Elbow extensor				X			X			X	
Sho+Elb flexor					X						X
Sho+Elb extensor						X					X

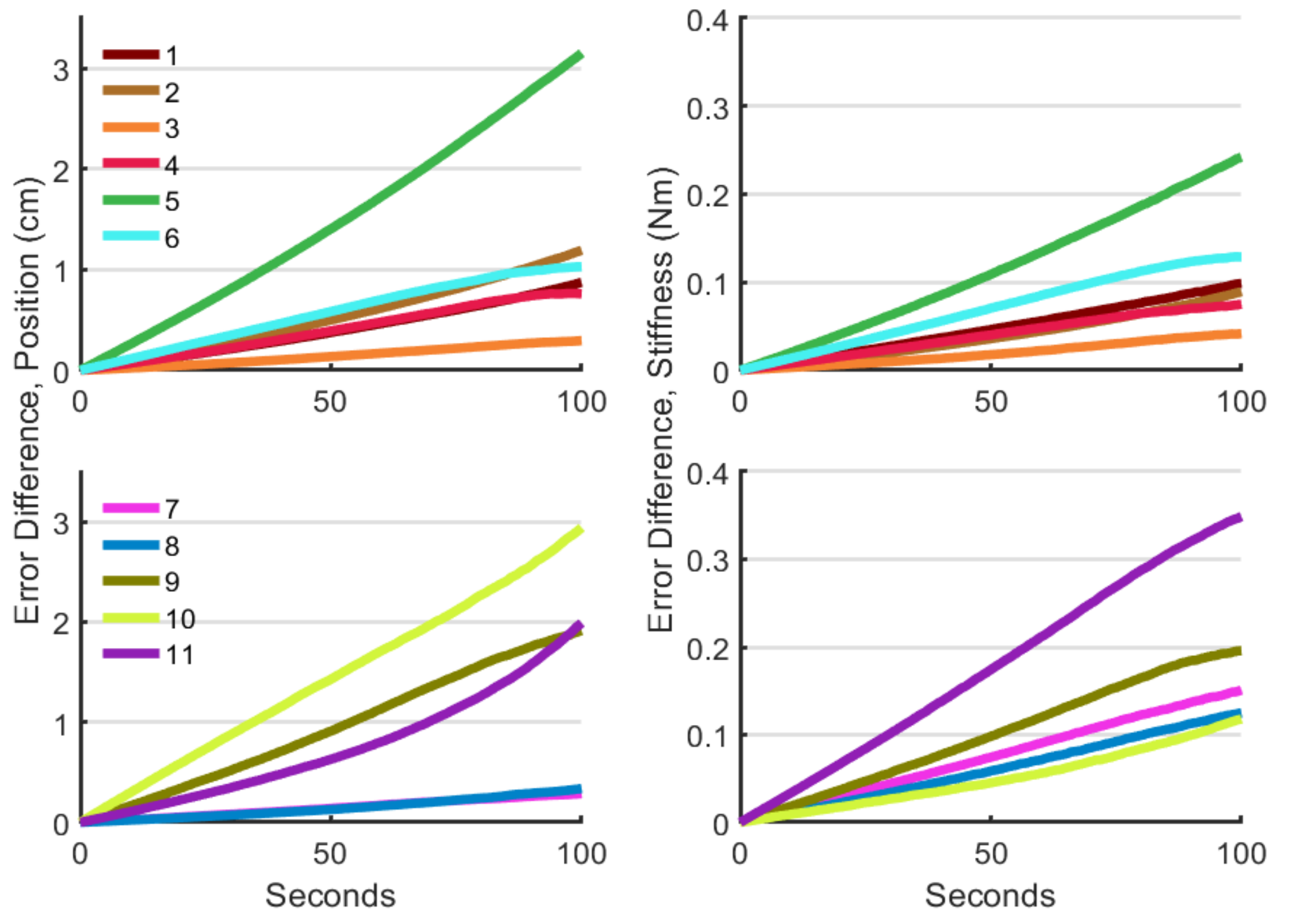
Right top: Differences in initial (*t*=1s) and final (*t*=100s) position & stiffness were collected when fatigue occurred using a standard lookup table

Right bottom: Reduction in errors over time when using a fatigue resistant lookup table (standard minus fatigue resistant errors). Lines show grand median across all positions/stiffness, color coded by fatigue condition

Errors in position & stiffness using a standard lookup table without fatigue compensation



Reduction in errors over time after compensating for fatigue



Translation to Human Application

This analytical approach could be applied to almost any user and FES system and is clinically realistic to implement

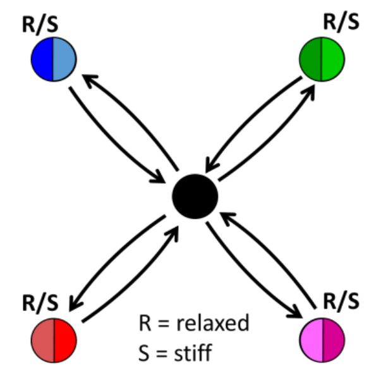
Systems such as the KINARM Exoskeleton Lab could be used to collect initial passive and active torques as well as resulting arm positions in response to stimulation.

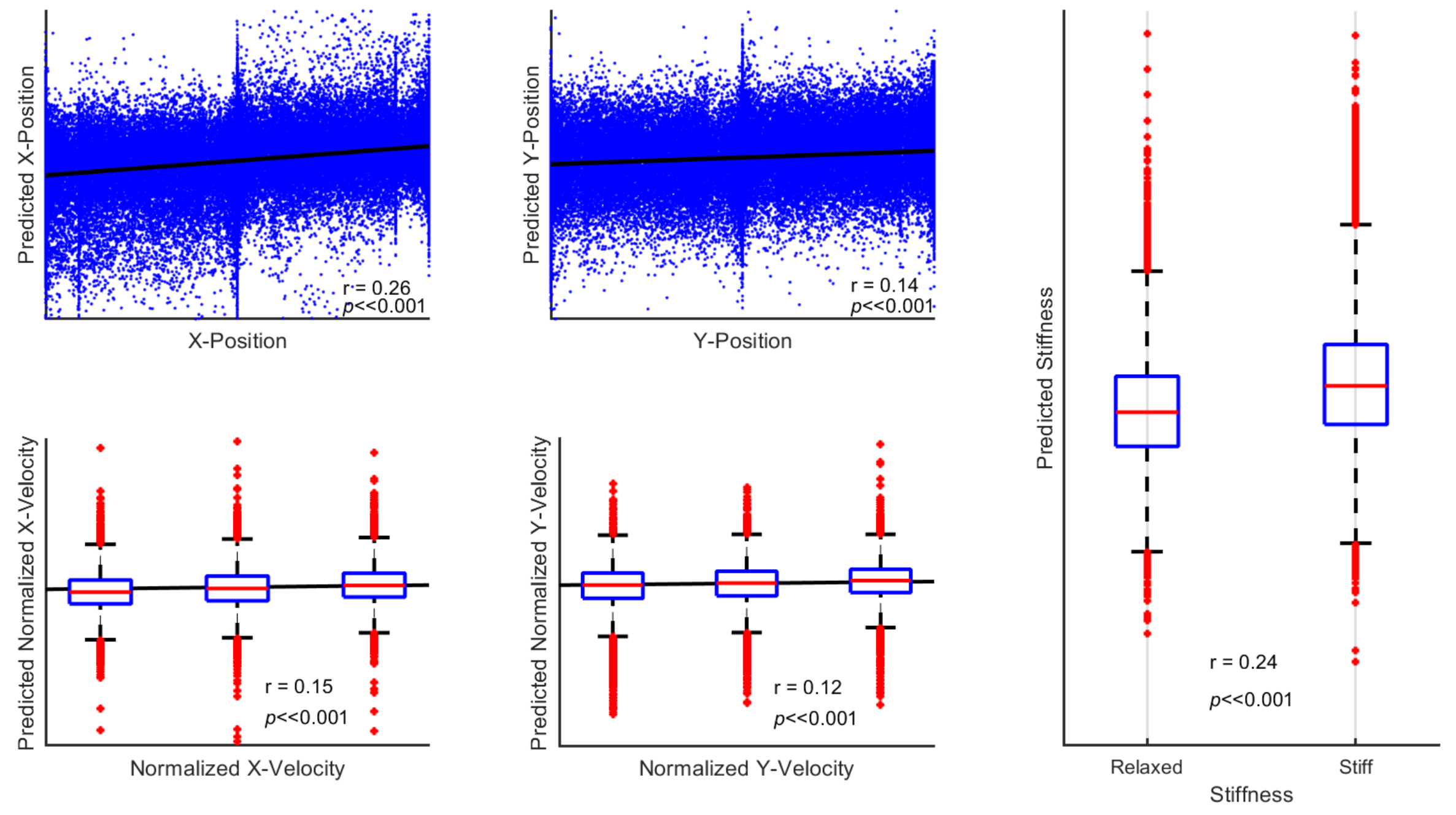
BKIN Technologies

Can we decode a volitional stiffness command?

Preliminary tests in the Reconnecting Hand and Arm to Brain (ReHAB) clinical trial suggest **yes!**

Participant RP1 (see poster 218.09) attempted open-loop center-out reaches to four targets with the limb stiff or relaxed. X, Y endpoint position and stiffness state were decoded from spike band power with a 10-fold cross-validation process.



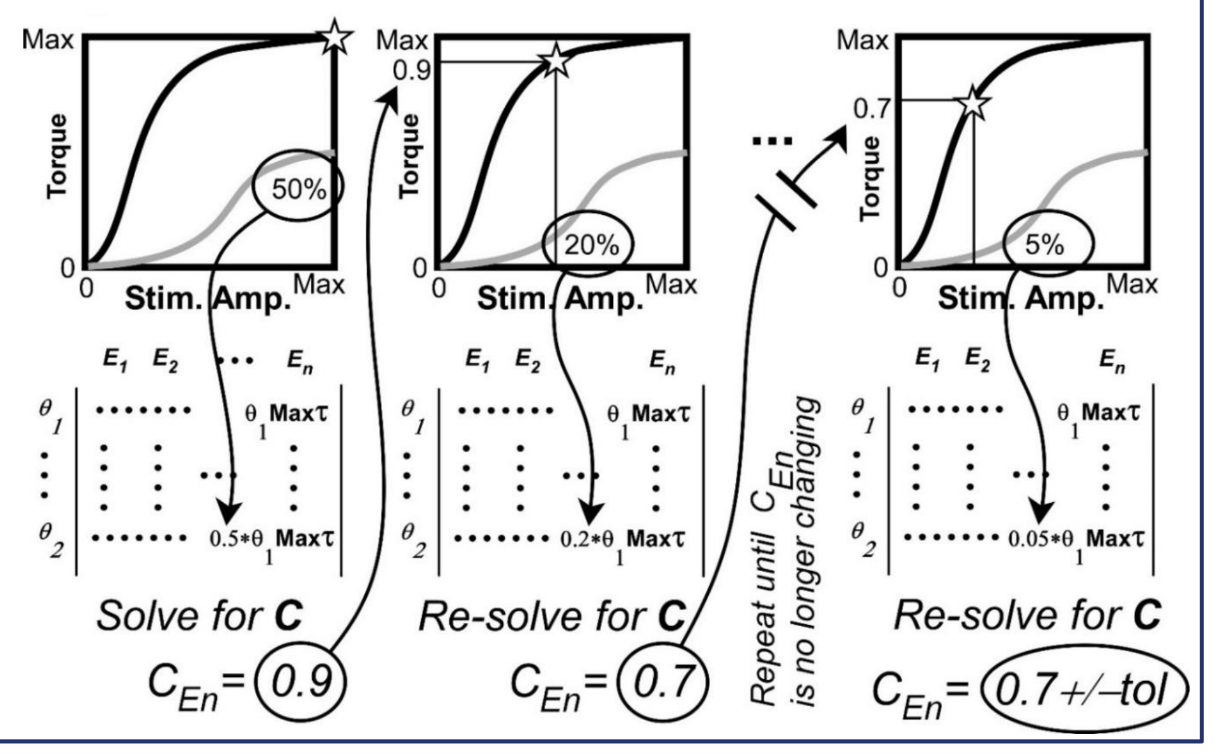


Multi-Nerve Electrode Compatibility

Lookup table building method can be modified to accommodate when single electrode channels activate multiple muscles *that each have their own unique activation profiles (e.g. nerve cuff and intraneural electrodes)*

Each electrode contributes one column in the ***A*** matrix. To account for the complex stimulation relationships of different muscles, an iterative process is used to hone in on appropriate ***A*** matrix parameters that allow one to solve for accurate stimulation values.

In example simulations with complex muscle activation profiles, appropriate stimulations could be identified in less than 10 iterations.



Conclusions

In this simulation study, we demonstrate an objective, clinically-feasible approach to building a controller for an upper limb FES system

- **Adding a 'stiffness' dimension to the controller turns an infinite search space into a simple system of equations that can be solved analytically**
- **Equations can be iteratively adapted to accommodate the complex multi-muscle activation profiles of nerve cuff or intraneural electrodes**
- **The 'lookup-table' controller can be built to de-emphasize easily fatigued muscles and rely more heavily on fatigue resistant muscles to minimize errors during arm use**

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Dynamic Arm Simulator was developed by RF Kirsch Lab and is now publicly available