# ENERGY OPTIMIZATION IN REACHING MOVEMENTS

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## INTRODUCTION

It is generally assumed that the CNS uses the many (kinematic and mechanical) degrees-of-freedom of the neuro-musculoskeletal system to minimize metabolic cost of movements. One reason why there is little evidence supporting this assumption is that energy optimizations of advanced musculoskeletal models (MSM) are computationally daunting due to the immense search space. However, with the ever increasing speed of (multi-core) CPUs, such optimizations might be within reach. Our goal is to use computer simulations and experiments to try to investigate if the CNS minimizes energy expenditure.

Our approach is to first use a MSM of the arm to optimize the muscle stimulation pattern (STIM) for reaching movements. Second, to construct a force field (FF) such that the optimized minimal energy movement path deviates substantially from the relatively straight paths observed experimentally in the absence of a force field (a null-field; NF). Third, have participants make reaching movements in the FF and test whether after training they revert to the 'normal' movement path observed in the NF, or to the predicted minimal energy path for the FF.

## METHODS

*Model*: The 2 DOF MSM [1] of the arm was actuated by six Hill-type muscles. Activation dynamics was modeled to describe the relation between muscle stimulation and active state. In addition, a model was used to calculate muscle energy expenditure[2]. *Simulations*: A Simulated Annealing (SA) algorithm was used to find STIM that minimized muscle energy expenditure for reaching movements without ($STIM_{NF}$) and with a FF ($STIM_{FF}$). The FF used was: $[Fx; Fy] = [-5\dot{\varphi}_s - 2\dot{\varphi}_e); 0]$ . The optimization criterion penalized the difference between desired and actual end-point, non-zero end-point velocity and acceleration, and muscle energy expenditure. *Experiment*: In a pilot study, one subject performed horizontal reaching movements along the surface of a desk, at shoulder height. A custom-built air sled was used to support the subject's arm against gravity while maintaining minimal levels of friction between the air sled and desk.

## RESULTS AND DISCUSSION

Not surprisingly, it was not straightforward to find parameters of both the optimization criterion and SA that led to converging solutions of consecutive optimization runs (we needed approx. $3{\cdot}10^8$ model simulations @ 400 ms/simulation). Preliminary results depicted in Figure 1 show the average optimized movement path of the hand (NF) of the 10 best solutions of 16 optimization runs (~320000 simulations per optimization run) as well as the predicted $STIM_{NF}$. The relatively small standard deviation of both kinematics and $STIM_{NF}$ is an indication that the found solution was somewhere near the global optimum. The mean predicted minimal energy path closely resembled experimentally observed paths. Even if the found solution is the global minimum, this does not necessarily mean that the CNS minimizes energy expenditure. Since the optimized and experimentally observed paths are identical, this result is compatible with any controller that adequately predicts such movement paths, even if that controller does not optimize energy per se (e.g. minimal torque change, optimal feedback control). Since the controllers are often discriminative with respect to control signals, it would be interesting to look at the relationship between optimized STIM and measured EMG, a topic for further research.

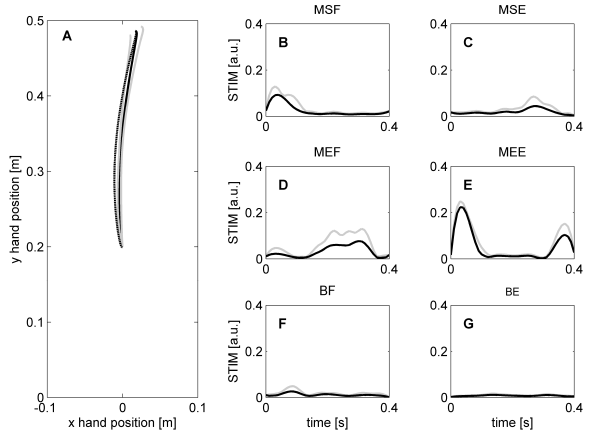


**Figure 1** A: Mean optimized path (black) ± std (gray lines) and average movement path of 1 subject (dashed line). B-G: Mean optimized $STIM_{NF}$ (black) + std (gray). MSF = mono-articular shoulder flexor; MEE = mono-articular elbow extensor; BE = bi-articular extensor.

For the present purpose, the FF must meet two criteria: i) it must lead to a minimal energy path that deviates substantially from that in a NF and ii) the minimal energy path in the FF should be distinct from that resulting from $STIM_{NF}$ in that FF. The constructed FF (see methods) did seem to meet these criteria. However, the standard deviation of both the optimized path and STIM were such that suggests that the solution is not close to the global optimum. The focus of ongoing research is first to find parameters that lead to a converging solution and then to investigate the relationship between the predicted kinematics and STIM and experimentally observed kinematics and EMG.

## ACKNOWLEDGEMENTS

Elizabeth Wilson and Jeremy Wong are greatly acknowledged for their valuable comments.

## REFERENCES

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2. Umberger BR, et al., Comp Meth Biom Biomed Eng **6**:99-111, 2003.