# Feasibility of Limb Postures and Slow Motions Throughout the Workspace with Muscles as Elastic Actuators

Sarine Babikian, Jason J. Kutch, Eva Kanso, and Francisco J. Valero-Cuevas, *Senior Member*

MUCH attention has been given to the mechanics and neural control of rapid limb movements, but the coordination of muscles to produce slow motions is not well understood. The aim of this paper is to identify the necessary biomechanical conditions that individual muscles must meet to produce slow and accurate limb motions. Our approach is to define feasible sets of muscle stiffness parameters for the limb to transition from one equilibrium posture to another in the workspace [1] [2], that is with quasi-static motions. In our 2-joint, 4-muscle planar finger model—and our 3-joint, 14-muscle group planar leg model [3] [4]—muscles are approximated as linear springs [5] with variable stiffness.

For both finger and leg tendon-driven systems, we prove that the postures in the workspace cannot be reached unless there exists an initial stretching within each muscle, i.e. an initial non-zero strain energy at rest. If this condition is present, slow motions are feasible and can be achieved through quasi-static transitions between equilibrium postures by adjusting muscle stiffness parameters. We resolve the redundancy of the tendon-driven systems by searching the nullspace of muscle stiffness parameters to select the optimal combination that produces a strain energy local minimum at that location. Fig. 1 shows the intensity of stiffness that each of the four finger muscles should provide in order to transition to every posture in the workspace, starting from an initial resting position. The figure explains that holding a given posture requires the stiffness of some muscles to be very low or inactive, suggesting that muscle inactivity is important in generating these postures.

Moreover, we explore the reachability set in the workspace and find that the necessary precision of control to achieve postures and motions throughout the workspace has a broad range as the size of the nullspaces varies greatly. These results begin to define the neuromuscular interactions within and among muscles necessary to regulate strain energy for stable and versatile function.

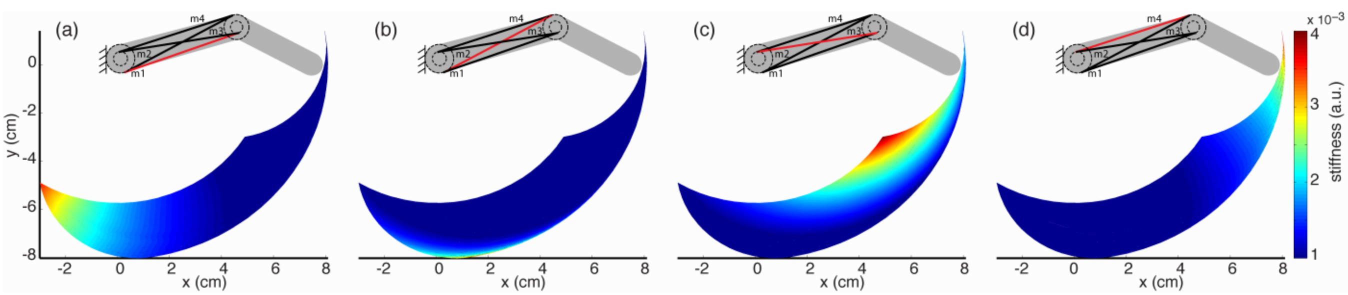


Fig. 1: Combinations of optimal muscle stiffness parameters necessary to achieve all endpoints in the finger workspace for: (a) muscle 1, (b) muscle 2, (c) muscle 3, and (d) muscle 4 (highlighted in red in finger model). Each single plot indicates the activity of a single muscle, which together with the shown activity of the rest of the muscles produces endpoint postures in the workspace.

## REFERENCES

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S. Babikian is with the Department of Biomedical Engineering (email: sbabikia@usc.edu).
E. Kanso is with the Department of Aerospace and Mechanical Engineering (email: kanso@usc.edu).
J. Kutch is with the Division of Biokinesiology and Physical Therapy (email: kutch@usc.edu).
F. J. Valero-Cuevas is with Department of Biomedical Engineering and the Division of Biokinesiology and Physical Therapy (email: valero@usc.edu).
All at the University of Southern California, Los Angeles, CA 90089 USA