Regulation of Human Arm Stiffness is Heavily Dependent on Existence of Muscle Synergies

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Abstract:

Much debate has arisen from conflicting experimental findings of limb impedance control during reaching movements—particularly about neural regulation of stiffness and its energetic consequences. Some find that the eccentricity and orientation of arm endpoint stiffness ellipsoids can be tuned arbitrarily in response to unstable force fields during reaching movements. Others come to nearly the opposite conclusion: that the ability of the nervous system to tune stiffness orientation is limited to around 30º rotation, and also that the mechanical consequences of changes in arm posture are responsible for much of the changes in eccentricity and orientation. We use novel theoretical analyses of tendon-driven systems and computational results to explain and reconcile these conflicting findings.

Introduction:

Limb stiffness control by the central nervous system has been a subject of much study and debate over the past 3 decades. Numerous experiments and theoretical analyses have been conducted on the biomechanical and neu- romuscular capabilities of the CNS to regulate endpoint stiffness of a limb. These studies chiefly analyze the stiffness of the hand in reaching-like postures, as this is a simple case to analyze and experiments with this limb are standardized and fairly easy to perform.

One set of experimental literature finds that the CNS can arbitrarily regulate the orientation and eccentricity of arm stiffness ellipsoids following training in order to perform a task more reliably and with less energetic expenditure than before training [1]. Another set of experiments concludes that the CNS cannot arbitrarily regulate endpoint stiffness, and that it is only able to rotate the orientation of the stiffness ellipsoid around 30º [2-4]. While these are very conflicting results, one large difference in the experimental conditions is that the former literature trains the arm and measures stiffness during reaching movements, while the latter literature measures stiffness without training in reaching movements.

Using the analyses developed in the robotics literature, we are able to resolve these divergent findings by computational experiments that offer explanations for both sets of results.

Methods:

We use a simplified planar arm model with 6 muscles similar to those that have been used in other theoretical and computational studies [5], shown in Figure 1.

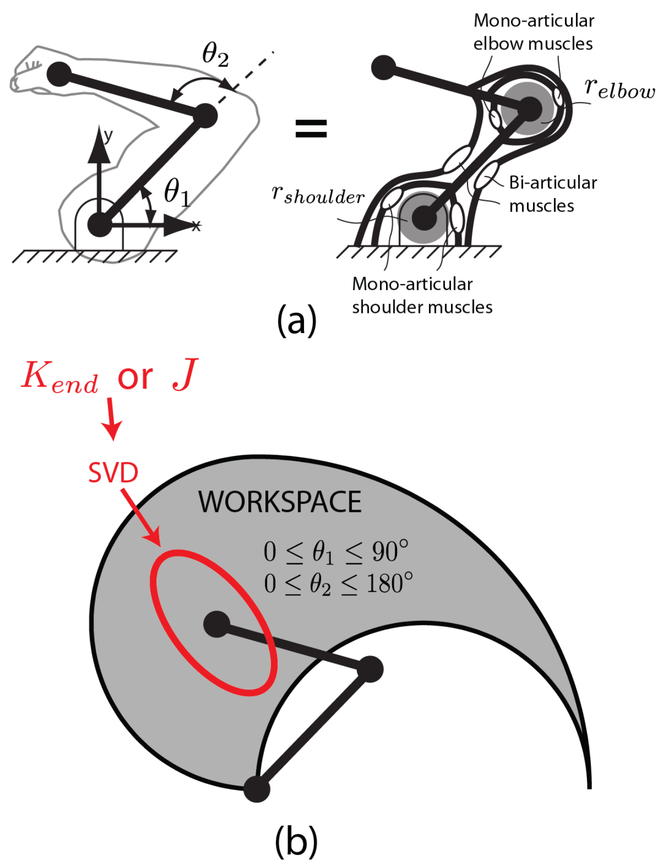

Figure 1: (a) Arm model. (b) Workspace and endpoint stiffness ellipse derived from SVD of the endpoint stiffness matrix.

The following equation relates endpoint displacements $\partial\vec{x}$ to reaction forces $\partial\vec{F}$, given the endpoint stiffness matrix K_{end}:

$$\partial\vec{F} = K_{end}\partial\vec{x}$$

We can use singular value decomposition of this endpoint stiffness matrix to visualize the stiffness characteristics as an ellipse, with the angle between the major axis and the x-axis (in the plane) being the orientation.

We can find this endpoint stiffness matrix from muscle co-contraction forces, the Jacobian J, and the moment arm matrix R using the following equation:

$$K_{end} = J^{-T} R(diag(\vec{F}_{muscles}))R^{T} J^{-1}$$

Reformulating this equation to a system of linear equations and utilizing linear programming, we are able to determine whether a specific endpoint stiffness orientation is achievable with or without muscle synergies. We tested orientations spaced 5º apart around a circle.

We implemented reported synergies (between elbow muscles and bi-articular muscles) among the muscles of the human arm [4] to determine the endpoint stiffness orientations achievable when these synergies are in place.

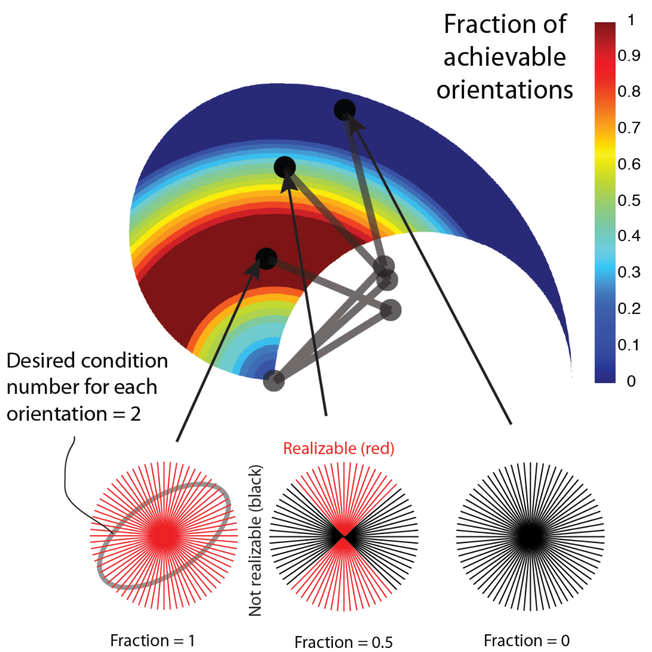

Figure 2: Achievable orientation fractions at various places in the workspace without synergies.

Results:

The results for the achievable orientations without synergies are shown in Figure 2.

Figure 3 shows the orientations achievable if the reported synergies are in place through 2 orders of magnitude of ratios between the synergies. The limited range of orientation flexibility is about 70º.

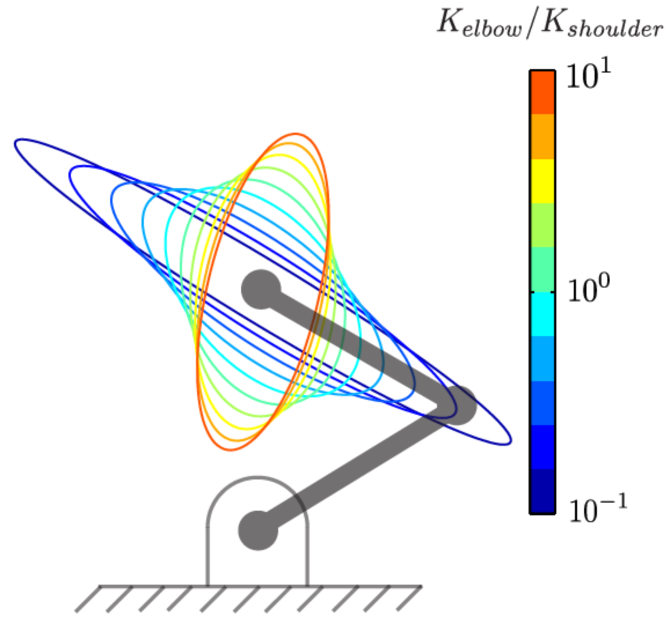

Figure 3: Achievable orientations fractions with synergies.

Discussion:

Our computational experiments without synergies support the data provided by [1] and other studies. Our experiments with synergies support the conflicting results of [2-4] and others.

Our results suggest ways in which future arm stiffness experiments may be conducted in order to analyze stiffness synthesis strategies used by the CNS such as synergies, energy minimization, posture adjustment, and active reflex pathways.

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Acknowledgments:

The authors gratefully acknowledge the useful comments from J. Kutch.

NSF Grants EFRI-COPN 0836042 and NIH Grants AR050520 and AR052345 to FVC.