Biomechanical Constraints on Equilibrium Point Control of Multi-Joint Arm Postures

Dan Song, Ning Lan and James Gordon

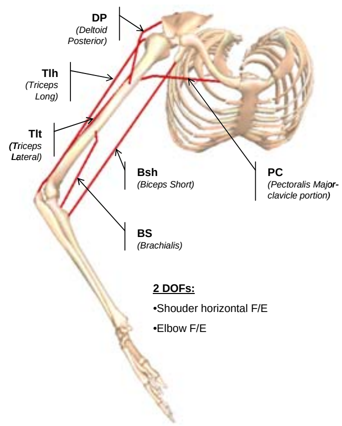
University of Southern California, Los Angeles, CA 90089
Web: www. http://pt.usc.edu/labs/cel/

INTRODUCTION

Modeling and simulation appear to reveal a plausible role of fusimotor command in controlling equilibrium point (EP) of the limb (Lan et al. 2005). In this study, we use a comprehensive sensorimotor model of the virtual arm (VA) (Song et al. 2006) to evaluate the impact of biomechanical properties on the EP control. The results help to understand the constraining effect of neuro-musculoskeletal properties of the peripheral plant on EP control in particular, and on motor control in general.

METHODS

A systems model of virtual arm in cascade with spinal reflex circuits was used in this simulation studies (Figure 1). The equilibrium points of the planar shoulder and elbow joints were steered by the gamma static fusimotor commands to the spindles of a pair of mono-articular antagonistic muscles acting at each joint. The virtual muscle (VM) implemented here captured the most realistic properties of mammalian muscle (Cheng et al. 2000). The musculoskeletal structure also incorporated realistic features of muscle moment arms at shoulder and elbow joints (Song et al. 2006). Spinal circuitry at the output of motoneuron pools included Ia stretch reflex, reciprocal inhibition, as well as Renshaw cell recurrent inhibition. Neural transmission delays and synaptic delays were considered in the spinal feedback loops. Reflex gains were selected



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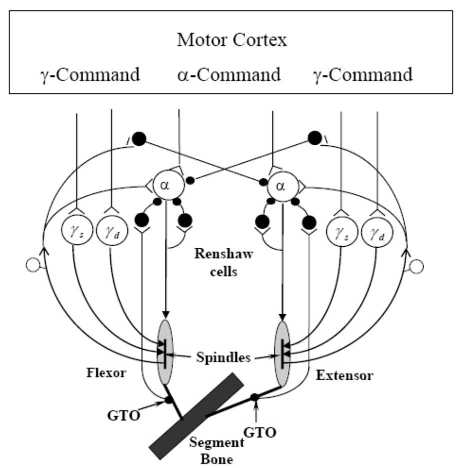


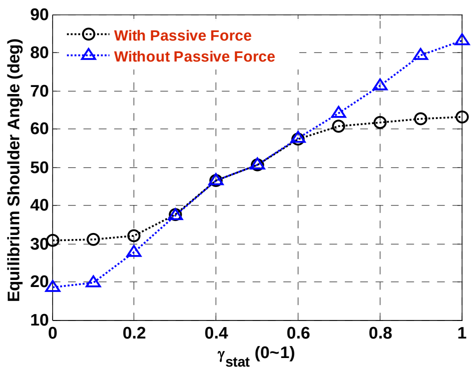
(b)

Figure 1, (a) six-muscle, virtual arm model, and (b) spinal reflex circuits that are implemented in the systems model for simulation.

so that the closed-loop response was stable.

RESULTS AND DISCUSSION

Simulation indicated that the choice of architectural parameters of the virtual muscles had a limiting effect on the range of equilibrium angles that can be modulated by the full range of gamma fusimotor control, i.e. from 0 ~ 1. This was mainly due to the fact that a low level of muscle activation was used for postural control under normal conditions. This tended to have a length-tension property combined with a moment arm profile together that produced little or no active force near the bounds of joint motion. Thus, passive forces overtook the active forces, and limited the effective EP range that can be achieved.



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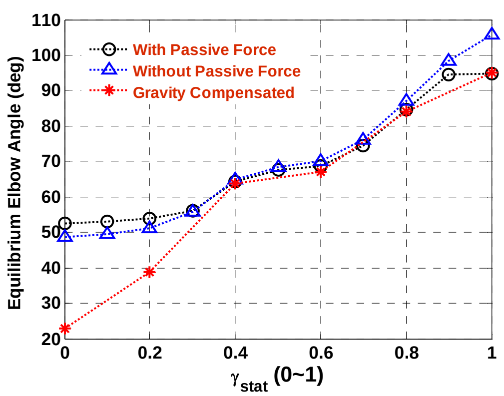

(b)

Figure 2, (a) the θ_{eq}–γ_s relation at shoulder joint when the elbow joint is fixed; (b) the θ_{eq}–γ_s relation at the elbow joint when the shoulder joint is fixed.

As shown in Figure 2, the range of equilibrium angle achieved with full range of γ command was limited by the presence of gravity influence and passive muscle force (Figure 2, with open circles). With gravity influence compensated at elbow and passive muscle force removed from all muscles, the range of equilibrium angle achieved was expanded significantly at both shoulder and elbow joints (Figure 2, with open triangles and stars). We believe that with proper tuning of muscle architectural parameters, particularly length-tension property, the range of equilibrium angle can be further expanded. However, these factors are realistic, and will present an inevitable constraint to the neural control of the brain.

CONCLUSION

This study illustrates the utility of realistic models to understand the limits of spinal sensorimotor control. Results suggest that, in order to overcome these biomechanical nonlinear constraints, an adaptive scheme for reflex gain control by supraspinal centers may be necessary in order to achieve a full range of EP control.

REFERENCES

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