OPTIMAL CONTROL MODEL OF HUMAN POSTURAL SCALING WITH BIOMECHANICAL CONSTRAINTS

[1,2] Sukyung Park, [3] Fay B. Horak and [1] Arthur D. Kuo
[1]Dept. Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA
[2]Dept. Mechanical Engineering, KAIST, Taejon, South Korea
[3]Neurological Sciences Institute of Oregon Health and Sciences University, Portland, OR, USA
email: sukyungp@kaist.ac.kr, web: me.kaist.ac.kr/~posture

INTRODUCTION

Human postural responses appear to scale as a function of perturbation magnitude to accommodate biomechanical constraints [1]. Scaling occurs in a gradual manner before discrete biomechanical constraints such as limitations on allowable ankle torque become active, implying a continuous neural representation of the constraints. We developed an optimal control model of human postural scaling using a constraint-penalized control objective, and examined whether the model could reproduce this gradually scaling of postural responses as perturbation magnitude increases.

METHODS

Fast backwards perturbations of various magnitudes were applied to 12 healthy young subjects (3 male, 9 female) aged 20 to 32 years [1,2]. Subjects were initially either standing upright or leaning forward on force platform and returned to their upright posture after perturbation stimulus. For each trial, kinematics and ground reaction force data were recorded and then used to compute net joint torques. We previously used system identification to determine subjects' feedback gains for each perturbation [1]. Here, we tested whether a single objective function could reproduce these gains, using a simple parametrization of the constraint dynamics.

We modified a previous linear feedback controller [3] for a 3-linkage biomechanical model of the body. Control gains were obtained by minimizing a control objective including a representation of biomechanical constraints. This representation determines whether the central nervous system (CNS) accommodates the constraints in a gradual manner or by an abrupt change of response. The maximum allowable ankle torque acts as a discrete constraint on postural feedback responses to support surface perturbations. If the CNS were to represent this constraint in a discrete manner, the CNS would uniformly scale postural responses with perturbations until the maximum ankle torque were reached. For larger perturbations, it would abruptly switch feedback gains to a different value to accommodate the discrete constraint. Neural networks are typically better suited to representing constraints in a more continuous manner, similar to a penalty function. If the CNS were to have a continuous representation, it would continuously scale control gains as a function of postural challenges so that the responses would be gradually adjusted to satisfy the constraints. We modeled this concept with an optimal control design. The objective included a penalty against violating the maximum allowable ankle joint torque constraint. We compared the model's feedback scaling behavior against the human experimental data.

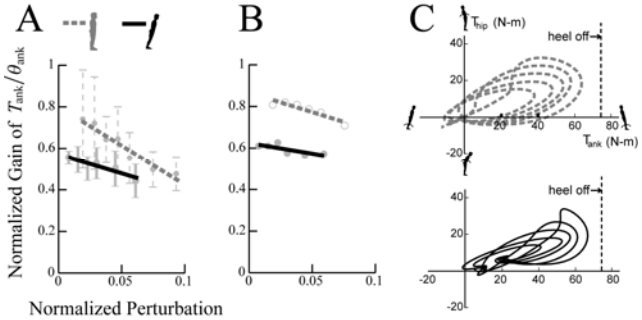

Figure 1: Postural scaling responses. (A) Empirical feedback gains scaled with perturbation magnitude as well as initial lean. (B) Feedback gains computed by optimization model also scaled gradually in a manner similar to data. (C) Joint torque trajectories computed from optimal control model. Gray dotted lines are for upright trials, black solid lines are for leaning trials.

RESULTS AND DISCUSSION

The optimal control model was able to roughly reproduce gradually-scaled postural responses in accordance with biomechanical constraints. The results suggest that the nervous system may represent potentially discrete constraints, such as a threshold torque before heel lift-off, in a continuous manner. It appears unnecessary for the CNS to store postural responses as a large number of muscle activation trajectories. Rather, a family of responses could be encoded by a much smaller number of feedback gains, whose scaling in turn could be encoded by a minimal set of parameters.

CONCLUSIONS

The constraint-penalized objective was able to reproduce the postural scaling with perturbation as well as initial lean. Gradual scaling of postural response by a penalty function implies that the nervous system may represent biomechanical constraints in a more continuous manner. The existence of the global objective based on the biomechanical model also suggests that the CNS is aware of body dynamics and flexibly scales postural response to accommodate biomechanical constraint, rather than discretely selects the preprogrammed responses.

REFERENCES

1. S. Park, et. al.. *Exp. Brain. Res*. **154**, 417-427, 2004.
2. F.B. Horak et. al.. *Gait & Posture.* **1**, 203-10, 1993.
3. A.D. Kuo. *IEEE Trans. Biomed. Eng.* **42**, 87-101, 1995.

ACKNOWLEDGEMENTS

This work support in part by NIH grants DC0231201 and AG06457. C. L. Shupert contributed to data collection.