A NEURO-MUSCULOSKELETAL MOTOR CONTROL MODEL WITH SOMATOSENSORY AND VESTIBULAR FEEDBACK

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INTRODUCTION

The use of dynamic systems theory to provide insight into neurophysiology has a long history (Barin, 1989; He et al., 1991; Kuo, 1995; van der Helm and Rozendaal, 2000; Iqbal and Roy, 2004). The motivation for this work is to develop a simple yet physiologically accurate model of human biomechanics and use it to study fundamental aspects of the central nervous system (CNS) control of posture and movement. Specifically, we are interested to explore answers to the following questions: a) how can a simple CNS control models be integrated into the mathematical description of the body derived from anatomy and physiology, and b) how does proprioception involving position, velocity, and force feedback support stability and facilitate control of posture and movement. To answer these questions, we consider a simplified characterization of the postural control system that broadly speaking has two components: one, representing the musculoskeletal dynamics in the sagittal plane, the other representing the sensors (muscled spindle, GTO, and the vestibular system), and the CNS. The model includes important physiological parameters such as muscle (active and passive) stiffness properties, length and velocity feedback from the muscle spindle, force feedback from GTO, vestibular feedback from the Otolith system, and transmission latencies in the neural pathways. Finally, a neural PID controller is assumed to represent the CNS analogue in the model theoretic framework.

METHODS

The human body is modeled as a multi-segment structure comprising of skeletal, muscular, and sensory subsystems. The musculoskeletal system model consists of four planar rigid-body segments that approximate sagittal plane biomechanics. The segments represent a bilateral symmetrical arrangement of the feet, legs, thighs, and head-arm-trunk (HAT) with stationary foot segment. The model parameters, i.e., the segment length, mass, centre of gravity and moment of inertia, are based on gross anatomical properties of the human body (Stroeve, 1999). The length of the stationary foot segment defines the base of support (BOS) in the anterior-posterior direction. The leg, thigh, and HAT each have a single-rotational degree of freedom.

The CNS commands and active force generation in the muscle are represented by a second order muscle model (Winter and Stark, 1985) that consists of: a) the excitation dynamics from the motor control signal to the neural signal, b) the activation dynamics from the neural signal to the active state, and c) the contraction dynamics that characterizes the force velocity relation in combination with the fiber and series elastic (SE) force-length relation. The active and passive muscle stiffness and viscosity are modeled as intrinsic muscle impedance. The dynamics of muscle spindle and GTO are characterized by constant gains. The corresponding block diagram for posture and movement control is shown in Fig. 1.

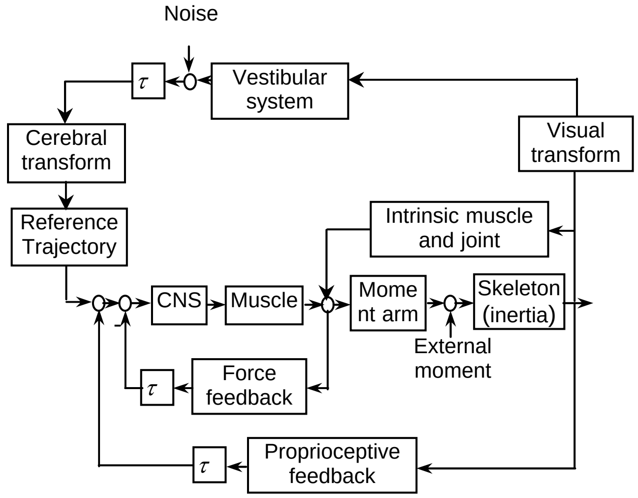

Figure 1: Conceptual block diagram of the human musculoskeletal control system with inherent muscle stiffness and viscosity, and physiological latencies in position, velocity, force, and vestibular feedback.

RESULTS AND DISCUSSION

For illustration purposes, an initial posture of $\varphi_i^0 = 0.15\times[\pi/6 \;\; -\pi/3 \;\; \pi/12]'$ rad and a terminal posture of $\varphi_i = [\pi/8 \;\; -\pi/4 \;\; \pi/16]'$ rad are assumed; such a trajectory may, for example, represent stand-to-sit movement. The resulting limb trajectories are plotted in Fig. 2. It can be seen that the kinematics are dynamically stable and attain the desired steady-state posture. Further, the movement has negligible overshoot (~ 0.1%), and a low settling time (≤ 1 sec).

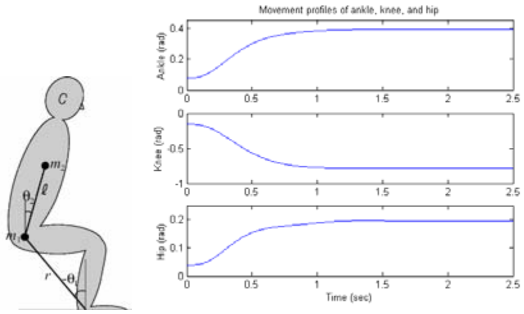

Figure 2: Physiological significance (left) and limb trajectories (right) for sit-to-stand transfer.

SUMMARY/CONCLUSIONS

Mechanisms of posture and movement control in the human body are investigated via a four-segment planar neuro-musculoskeletal model The model includes position, velocity, force, and vestibular feedback, the intrinsic stiffness properties of the muscle, and the physiological latencies of the motor servo system. The CNS control of the postural stabilization process is represented by three autonomous PID controllers, one each for the ankle, knee, and hip joints (Roy and Iqbal, 2006). Our simulation results confirm that the anatomical arrangement, active muscle stiffness, force and vestibular feedback, and physiological latencies of the body segments play a major role in shaping motor control processes in the human body.

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