POSTURE, EQUILIBRIUM, AND POSTURAL STABILIZATION

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Contents

Summary

Postural equilibrium (or balance) involves actively maintaining the chosen body configuration against gravity, and internal or external disturbances. Quiet standing implicates incessant postural adjustments, the involuntary movements aimed to counter multidimensional disturbances to the standing posture. Standing humans over moving support surface have been observed to use ankle and/or hip strategies to regain balance. Postural stability constitutes an important attribute of the musculoskeletal-proprioceptive apparatus. It is enabled by the biological servomechanism called lower-level motor servo that generates reflexes aimed and relieving muscle tension. Quantifiable measures of postural stability include center of mass (COM) or center of pressure (COP) relative to base of support (BOS), extended COM position, and feasible stability region (FSR) in the COM phase plane. Passive viscoelasticity of the musculo-tendon complexes (MTCs) is a major contributor to postural stability. Stability augmentation entails persistent central nervous system (CNS) involvement via spinal reflexes, internal model control, and anticipatory postural adjustments (APA). Active control of muscle stiffness and tone relies on proprioceptive feedback to dynamically modulate muscle afferents. Yet, how the CNS mitigates the destabilizing effects of neural transmission delays and muscle lags remains unclear. Mathematical models have often been used to provide insight into neurophysiology. Control of balance in human upright standing is particularly well suited for modeling, and is also a popular experimental paradigm. Analytical models based on behavioral experiments have shown that human

stance control can be explained by continuous sensory feedback, sensorimotor integration, and the use of internal models. Inverted pendulum (IP) type models of postural control, though simplistic in construction, are popular among researchers. Analytical modeling studies employ control theoretic analogues, such as a proportional-integral-derivative (PID) controller, to represent the decision making modalities in the CNS. In this chapter, we aim to provide a broad discussion of the neuro-physiological bases of postural equilibrium, stability, and control in the backdrop of neuroscientific research and mathematical models.

1. Introduction

Human posture refers to the static disposition of limbs and body parts. Examples of static posture include standing (also referred to as stance), sitting, lying down, etc. Transition from one static posture to another entails movement, which may be categorized as postural, voluntary, skilled, ballistic, phasic, etc. At a broad level, goal-directed voluntary movements can be distinguished from postural adjustments that are initiated in response to internal or external perturbations to the standing posture. While postural movements are usually performed in the range of 5-10 Hz, skilled voluntary movements can be performed at much higher speeds. Skilled voluntary movements exhibit smooth kinematic profiles, i.e., S-shaped angular position profiles, nearly constant velocity profiles, and biphasic acceleration profiles that indicate force generation in the agonist and antagonist muscles. Static posture is a special case of postural equilibrium, which implies a balance of forces and moments acting on the body. Maintenance of postural equilibrium requires muscle activations to counter the gravitational torques acting on the limbs. For example, the standing posture is achieved through the activation of lower extremity muscles to counter the moment generated by the vertical ground reaction force acting through the COP. Static equilibrium also requires the center of gravity (CG) of the whole body to be positioned over the BOS – the area under the two feet. Further, in the context of movement, the dynamic equilibrium refers to the balance of forces and moments (including inertial moments) on the body when in motion. For nonlinear systems, dynamic equilibrium implies that motion is restricted to a closed curve in the phase space. In biomechanical systems, a closed phase space orbit may only be achieved for certain phasic movements (e.g. walking). The COM in the case of dynamic equilibrium may not be restricted to the BOS. For example, COM during walking is located outside of the BOS 80% of the time.

The neuro-physiological processes involved in regulation of posture and voluntary movement in humans and vertebrates include: the CNS comprising brain and spinal cord; the peripheral nervous system (PNS) comprising afferent and efferent pathways; the musculoskeletal system comprising skeleton driven by the muscle-tendon actuators; and, the sensory system composed of a variety of sensory receptors, including muscle spindle (MS), Golgi tendon organ (GTO), joint, subcutaneous, somatosensory, and mechanoreceptors. These collectively describe the neuro-musculo-skeletal control system (NMSCS), comprising musculoskeletal and proprioceptive elements, that plans, organizes, executes, and regulates postural and voluntary movement. The state of the musculoskeletal system may be represented via such variables as muscle length, tone, stiffness, rate of shortening, etc. These are monitored by a distributed net of sensory receptors, and transmitted via afferent pathways to the CNS, where they are integrated and processed with other proprioceptive information and stimuli (tactile, somatosensory, visual, and vestibular) to generate descending commands. These constitute motor neuron firing rates are transmitted over efferent pathways to the muscle actuators where they energize the motor units (MUs), each comprising of a motor neuron and the muscle fibers it stimulates. The ensuing contractile action by muscle fibers facilitates movement in support of the intended task. Active control of movement trajectory is achieved through continuously varying the firing rate commands issued to the motor neurons (MNs) of antagonist muscle pairs. Primary movement stability during trajectory formation is provided by the spring-like behavior of synergistic muscles and the resulting mechanical stiffness of the muscle-joint structures. While stiffness is maintained at constant values during static postural synergies, it is dynamically varied during skilled voluntary movements. For example, during walking stiffness is maximized at a time in the step cycle when the extensors must support the weight of the body.

Motor control refers to the modalities of posture and movement that are controlled by central commands and spinal reflexes. Motor control of postural and voluntary movements is executed as a series of motor programs stored in the CNS long-term memory (Figure 1). These programs refer to neuronal networks in the CNS that are designed to handle the basic motor repertoire required for survival, including locomotion, posture, eye movements, breathing, chewing, swallowing and expression of emotions. Motor programs for pre-planned actions specify muscles to be used, muscle tones, sequencing of contraction, relative timings, and durations of contractions. These commands are transmitted with precise timings via descending pathways to the motor units involved as the movement unfolds. The motor programs allow the movements to be carried out without explicit, conscious CNS control. Programs for goal-directed movements reside in the association cortex. The motor cortex translates these programs into mechanical stiffness at the joints (hold program), movement direction, velocity and end points (trajectory or move program). The spinal cord implements these programs by setting the muscle tone and stiffness, along with the sensitivity of the primary sensory organs, the MS and the GTO. The concatenation of simple motor programs into fully formed motor plans requires afferent feedback to inform CNS of the success of each program unit, enabling it to modify any errors in execution, before proceeding with the plan for the next stage. Afferent signals from MS convey length and velocity of the contractile element (CE), and afferents from GTO convey information about muscle tone. While mechanisms of postural and voluntary movement are similar in nature, we will concentrate on the former in the discussion that follows. Although neural mechanisms regulating postural control are unknown, evidence suggests that the hierarchal controller for postural adjustments resides in supraspinal circuits, possibly in the brainstem.

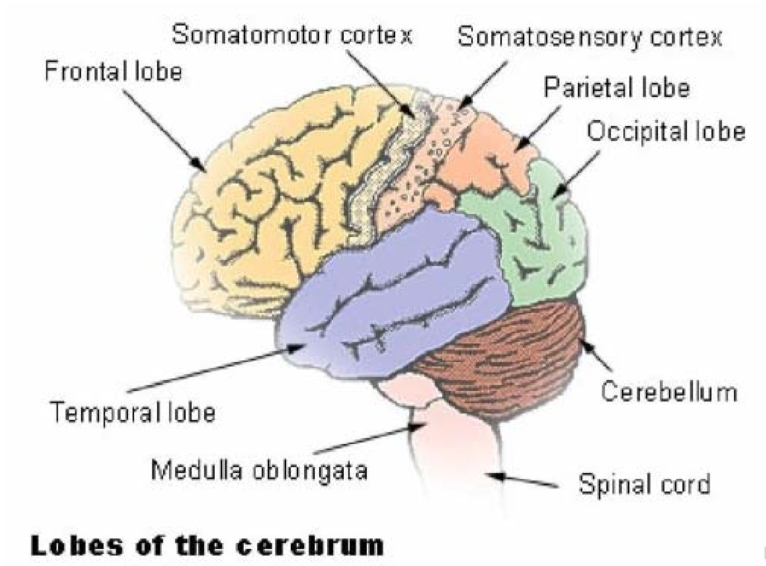

Figure 1. The human brain: Cerebrum lobes, Cerebellum, Somatomotor and Somatosensory cortices. The motor cortex and cerebellum, in particular, play a lead role in the coordination of postural and voluntary movement (from SEER Training Modules, *Brain*. U.S. National Institutes of Health, National Cancer Institute, <http://training.seer.cancer.gov/brain/tumors/anatomy/brain.html>, in public domain).

The use of control-oriented mathematical models to provide insight into neurophysiology has a long history. Researchers have often used mathematical modeling of the physiological apparatus aided by application of analytical methods to answer questions about physiological behavior. Control of balance in human upright standing is particularly well suited for modeling, and is a popular experimental paradigm. Researchers have also discovered that simplified representation of postural dynamics and computation of a minimal set of stabilizing feedback gains using system identification methods, allows them to make reasonable predictions of natural motor behaviors. Biomechanical models of varying complexity have been widely employed in the study of posture and movement. Whereas, researchers have extensively studied sensorimotor systems for at least a century, mathematical descriptions of these systems have emerged only in the past few decades.

Our intent in this chapter is to discuss the neuro-physiological mechanisms of postural equilibrium, stability, and control using neuroscientific research and biomechanical models as tools to understand the underlying neurophysiology. It would not be possible to provide and exhaustive treatment of the subject; the interested reader is referred to the many excellent references provided at the end of the chapter. The rest of the chapter is organized as follows: mechanisms of postural adjustments and stability are introduced in Section 2, which also introduces'principal determinants of postural stability; active and passive mechanisms of postural stabilization are explained further in Section 3, which includes a discussion on the biological servomechanism known as lower-level motor servo; neuroscientific and mathematical models of the postural control, including internal models, inverted-pendulum models, and multi-segment models are described in

Section 4; controller models for postural movements are discussed in Section 5; finally, conclusions are drawn in Section 6.

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Biographical Sketch

Kamran Iqbal was born in Multan, Pakistan. He earned his Bachelors in avionics engineering from NED University, Pakistan in 1980. He later earned his MS and Ph.D. in electrical engineering, in 1988 and 1992 respectively, from the Ohio State University, Columbus, Ohio. He also earned his MBA from the Ohio State University in 1991.

Dr. Iqbal taught as Instructor at Air Defense Training School from 1980 to 1981, and worked as Avionics Supervisor from 1980 to 1986. During his graduate studies, he worked as research assistant for the department of electrical engineering, and the department of industrial and systems engineering from 1989 to 1992. He was employed as assistant professor in the College of Aeronautical Engineering, Pakistan from 1993 to 1996, and as assistant professor in the Faculty of Electronics Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan from 1996 to 1997. He was a visiting scholar at the Department of Electrical Engineering, the Ohio State University in summer 1996. He later worked as research associate in the Programs for Physical Therapy, Northwestern University, Chicago, Illinois from 1997 to 1999. Before coming to the University of Arkansas at Little Rock in 2000, he taught as lecturer at the Department of Electrical Engineering, California State University, Fullerton and the Department of Electrical Engineering, University of California, Riverside. Since 2000, he has been employed with the Department of Systems Engineering, University of Arkansas at Little Rock where he currently holds the rank of tenured professor and serves as associate chair for the department. His research interests include biomechanical models of posture and movement, postural stability, motor control, stability and control in dynamic systems, computational intelligence, robotics, and biomedical signal processing and modeling.

Dr. Iqbal is a senior member of IEEE (Computational Intelligence, Control Systems, Engineering in Medicine and Biology, and Systems, Man, and Cybernetics societies), member of IET (UK), IASTED, INCOSE, IAENG, Sigma Xi (President Elect for the Central Arkansas Chapter), life member of Pakistan Engineering Council, and past member of AIAA and ASB.