Measuring how humans control balance and orientation during stance and gait

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I. BACKGROUND

Humans use orientation and motion information derived from sensory systems to generate corrective motor actions that resist the destabilizing effects of gravity, other external perturbations, and internal perturbations (sensory and motor noise) in order to maintain stability during stance, to achieve dynamic stability during gait, and to maintain a desired body orientation during stance and gait. The primary sensory systems contributing to balance control are the proprioceptive system (signaling motion of body segments relative to one another and to external contact surfaces), visual system (signaling head motion relative to the visual environment), and vestibular system (signaling head motion in space). In principle, the central nervous system could combine information from the head-mounted visual and vestibular sensors with multi-segmental proprioceptive cues in order to derive an estimate of body center-of-mass (CoM) position. In quasi-static conditions of quiet or mildly perturbed stance, stability is assured if the motor actions maintain the CoM over the base of support. In dynamic conditions stable gait requires that natural body dynamics and/or motor actions constrain the CoM motion to follow a nominal, repeating trajectory and to return to that trajectory following a perturbation.

If it is desirable that the balance control mechanisms employed in humanoid robots mimic those of humans, then three tasks need to be accomplished. First, it is necessary to understand the mechanisms that contribute to balance control in humans. Second, the humanoid robot must implement a balance control scheme that provides some reasonable approximation to human balance control. Third, measurement methods must be developed that capture the key aspects of balance control so that the efficacy of balance control mechanisms implemented for robots can be assessed and compared to those of humans.

Unfortunately, our collective knowledge about human balance control is incomplete and is particularly lacking for balance control during gait. Nevertheless, using methods developed in our laboratory, we have come to understand some important features of how humans control their upright stance and, more recently, we have applied these methods to begin to understand how balance is controlled during walking gait and during a gait-like task of stepping-in-place (SiP). My presentation will first describe the methods we have applied to characterize both sagittal and frontal plane balance control during quiet stance, and then will describe methods and results from our preliminary investigations of balance control during gait. The methods that our laboratory has developed can easily be applied to test the balance of humanoid robots.

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II. METHODS TO CHARACTERIZE BALANCE CONTROL DURING STANCE

A large literature exists that describes how investigators have quantified balance by measuring spontaneous (i.e., non-perturbed) body sway while manipulating access to visual information (eye open or closed) and/or proprioceptive information (standing on foam). Balance control has also been measured by characterizing responses to transient perturbations such as sudden translations or rotations of the stance surface. While results from these investigations provide some information on balance control and the changes that occur with various pathologies, they have been only partially successful in revealing information about the mechanisms responsible for the continuous regulation of balance.

Our laboratory has found it more informative to use continuous, wide-bandwidth pseudorandom perturbations (e.g., surface or visual surround rotations) and then to apply engineering system-identification methods to characterize the dynamic properties of the stance control system [1,2]. We have found that CoM sway responses to pseudorandom perturbations are consistent with that of a linear dynamic system under a given set of test conditions. This linear behavior is true for perturbations that evoke body sway in both the sagittal and frontal planes. We have primarily analyzed data using spectral analysis methods to calculate frequency response functions (FRFs) expressed as gain (ratio of sway amplitude to stimulus amplitude) and phase (timing of sway relative to the stimulus) functions. The FRF characteristics (primarily the gain) typically change as test conditions change. For example with surface-tilt stimuli, the FRF gain decreases with increasing stimulus amplitude. This amplitude-dependent behavior is due to a sensory re-weighting phenomenon whereby the balance control system changes the proportions that the various sensory systems contribute to the generation of corrective torque [1,2]. Sensory re-weighting occurs in both sagittal and frontal plane balance control, but frontal plane control is more complex in that sensory re-weighting also depends on stance width [3]. Experimental results in humans with normal sensory function are consistent across subjects and show characteristic, quantifiable changes in dynamic behavior across test conditions. The methods we have used could easily be applied to humanoid robots to determine the extent to which the robots balance behavior during stance matches that of a human.

III. METHODS TO CHARACTERIZE BALANCE CONTROL DURING GAIT

We recently applied methods similar to those we used to characterize balance during stance to understand how humans control frontal plane dynamic balance and body orientation during walking gait and SiP. It is recognized that active control is necessary to maintain the dynamic stability of the roll motions that occur during gait [4]. Kuo (1999) considered several mechanisms that could be used to stabilize frontal plane motion and concluded that adjustments in step width provided an efficient mechanism. We performed experiments where subjects performed a SiP task while the surface was continuously rotated to perturb body motion in the frontal plane. We wanted to determine whether balance control phenomena observed in stance control, such as sensory re-weighting, were present under the dynamic conditions of a gait task. We furthermore expected to see that subjects adjusted their step width in a systematic manner to compensate for the applied perturbations.

We found clear evidence for sensory re-weighting in the control of body orientation during SiP. However, we found no evidence for step-width modulation. Rather, subjects adjusted their step timing to regulate frontal plane body motion during the stepping task. While step-width control has been considered to be an effective mechanism for frontal plane balance control during gait, more recently Maufroy et al. [5] investigated the regulation of step timing, which they referred to as "walking phase modulation", for the control of frontal-plane stability. Our results are consistent with step-timing regulation being an important contributor to orientation control and dynamic stability in our SiP task and in preliminary results from a walking task where frontal-plane balance perturbations were provided by galvanic vestibular stimulation [6]. Our results give insight into the mechanisms that humans use to control stability in the frontal plane during gait and indicate that such a mechanism should be included in the balance control scheme of a humanoid robot designed to mimic human behavior. Step-timing metrics are easy to measure and to use for comparison of robot balance performance to human performance.

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