Heads will roll! Sensory integration model of postural response to lateral visual perturbations.

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Motivation:

Human action relies on sensory perception, but perceptions can be deceiving. The driver of a stationary car may think he is moving backwards when the neighboring car creeps forward. The pilot of an aircraft in a sustained turn may believe he is at level flight even though his aircraft is still banking. Visual, vestibular, and proprioceptive systems monitor and encode the shifty external world, but how does the brain trust this information to contend with disturbances or dynamic uncertainties?

Postural responses are driven by multiple sensory modalities, each of which has its own dynamics. A person sitting in an optokinetic drum equates eye velocity to flow velocity [Cohen 1981], but a person standing in a moving visual field does not equate body velocity to flow velocity [Keshner 2000]. Instead of following the visual frame to the ground, the elicited postural behavior is to lean in the direction of the optic flow without falling over. In an effort to understand the mechanisms behind this tilt phenomenon, our research examines the postural response due to roll-axis visual field motion during quiet standing.

State of the Art:

The central nervous system (CNS) integrates sensory inputs to estimate body position and velocity. This may be modeled by an optimal estimator using noisy measurements [Kuo 2005]. When each sensory channel is assigned a set weighting, the dynamics of the estimator model are linear.

These weightings may vary as channels degrade or as the sensory environment changes [Oie 2002]. Hence, sensory reweighting is a proposed nonlinear model that allows for sensory weights to change dynamically depending on sensory condition [Oie 2002]. These models can involve a weighted addition of contributions from the three sensory inputs [Peterka 2002], extend estimator models to include an internal model of the environment [Carver 2005], or use adaptive Kalman filters [van der Kooij 2001]. However, sensory reweighting might not be necessary to explain fundamental postural behavior. Can the tilt dynamics then be captured with a linear estimator?

Own approach:

This study models the CNS as a simple optimal estimator and demonstrates that estimator dynamics alone can account for postural response within the visual surround environment. The model has three sensory channels as inputs and produces an estimate of body tilt as output. The estimator is built from a plant composed of the visual, vestibular, and somatosensory systems. The visual system is assumed to measure angular velocity while the proprioceptive system and otoliths measure body angle. The semicircular canals are modeled as a high-pass filter with dynamics dominated by the cupula time constant [Robinson 1977]. For simplicity, the estimator model assumes accurate knowledge of plant dynamics with process and measurement noise covariance of one. This yields a third-order system with first-order, low-pass filter dynamics.

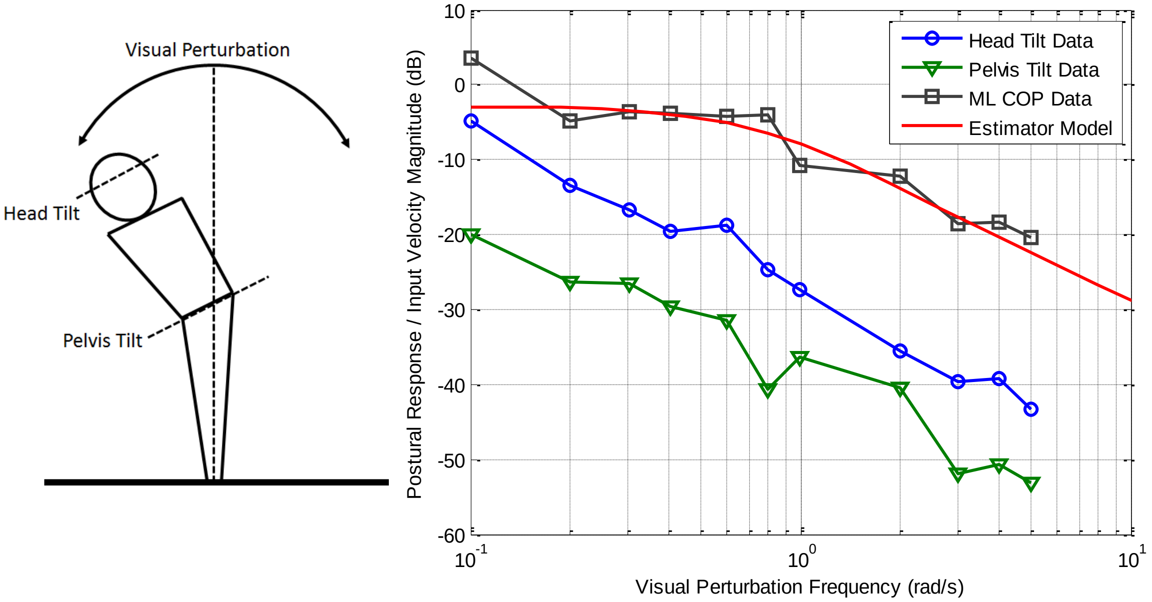
We performed an experiment to test the estimator model. Subjects viewed an optic flow field of random dots rotating sinusoidally about their head in the roll direction at a range of frequencies from 0.1 rad/s to 5 rad/s. The sinusoidal amplitudes were chosen to maintain a fixed maximum dot velocity across all frequencies. The mediolateral (ML) components of the head and pelvis tilt and center of pressure (COP) were recorded using the Vicon Nexus system. The ratio of body tilt and COP magnitude to input velocity magnitude was determined at each frequency to build a frequency-based representation of postural response to sinusoidal perturbations for comparison against the estimator.

Discussion:

The estimator model appears sufficient to demonstrate sensory integration, specifically with visual stimulation. Figure 1b depicts the averaged results of head tilt, pelvis tilt, and ML COP magnitude from three subjects. The experimental magnitudes follow the estimator’s first-order trend towards lower magnitudes as frequency increases, suggesting that the dynamics of the simple estimator account for postural response even within the visually changing environment. Further comparisons will examine the phase frequency response, where the model predictions may be compared with experimental data to corroborate the trends in the magnitude plot. Additional comparisons are needed between this estimator and alternative models and against additional experimental data.

Since the visual field rotates about the subject's head, the sensory conflict could potentially be resolved only in head tilt, with the other segments kept vertical. However, the pelvis data shows otherwise, revealing differences in how the body segments respond to visual perturbation. Perhaps the sensory conflict between the visual system and the vestibular and proprioceptive systems limits head tilt and propagates the position error down the body. Lower in the body, however, there is more ground-referenced proprioceptive information that decreases position error. Hence, the sensory conflict still manifests in pelvis tilt, but to a lesser degree than in head tilt.

There were limitations in our experimental method. The sinusoidal perturbations were of a single frequency and are therefore potentially predictable to the subject. Would a sum of sinusoids perturbation yield the same effect in magnitude as shown in Figure 1b for the single sinusoid conditions? Answering these questions and further study of the estimator model will yield important insights into sensory integration and a better understanding of postural control behavior in both standing and walking.



(a) (b)

Figure 1: (a) Example body tilt behavior; (b) Frequency response of the transfer function with postural position as output and visual field angular velocity as input (N = 3). The postural response transfer function was determined by the magnitude ratio of head tilt, pelvis tilt, and ML COP data to visual input velocity. The response magnitudes were calculated for each subject at a range of stimulus frequencies from 0.1 rad/s to 5 rad/s and then averaged.

Format: Talk

Keywords: posture, vision, sensory processing, optimal estimator

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