Sensory dead zones and sampled time delayed feedback in human balance control

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The morbidity and mortality associated with falls in the elderly is a major concern for modern industrialized countries. Consequently identifying the mechanisms that the nervous system uses to stabilize balance has become an important problem. Here I review the effects of three essential components of neural feedback on human balance: 1) a conduction time delay, 2) a sensory dead zones and 3) time sampling. The conduction time delays arise because axonal conduction velocities are finite and hence it is necessary to take into account the time between when the nervous system detects an error and then act upon it. All sensory receptors in the nervous system have a sensory dead zone, namely there is a threshold below which changes in sensory input are not reflected by a change in output. As a consequence control becomes intermittent since feedback switches between ON and OFF depending on whether the controlled variable is above or below the sensory threshold. While this nonlinearity has no effect on large-scale stabilization in linear systems, it can lead to the generation of periodic oscillations and even low amplitude chaotic fluctuations referred to as microchaos. Which of these dynamical behaviors occurs depends on how the feedback is time sampled. Neural feedback is time sampled as a consequence of frequency dependent neural encoding and the presence of physiological refractory times. When the feedback is sampled continuously, the combined effect of the dead zone and time-delayed feedback is to produce a limit cycle oscillation whose amplitude scales as a function of the magnitude of the sensory threshold. When the feedback is time sampled, microchaotic fluctuations can appear. In order to demonstrate this phenomenon the dynamics of the quantized and sampled Hayes equation are investigated as function of the feedback sampling frequency. This equation describes the dynamics of an unstable scalar dynamical system stabilized by a time-delayed, switching-type negative feedback controller. It is shown that the maximum Lyapunov exponent, $\lambda_{\max}$, is positive and is inversely proportional to the sampling frequency. In other words the lower the sampling frequency the more positive $\lambda_{\max}$. Thus the neural feedback for balance control resembles a sampled data system and is capable of generating microchaos dynamics in much the same way as occurs when digital time-delayed feedback is used to control a continuous mechanical system (G. Stepan, J. G. Milton and T. Insperger (2017). Chaos 27: 114306). The fluctuations in the vertical displacement angle during quiet standing with the eyes closed exhibit a positive Lyapunov exponent, $\lambda_{\max}$, a measure typically associated with a chaotic dynamical system (L. Ladislao and S. Fioretti (2007). Med. Bio. Eng. Comput. 45: 679). Thus the above observations suggest that human postural sway chaos may arise from the interplay between time delayed feedback, a sensory dead zone and the frequency dependent nature of neural encoding in the peripheral nervous system.