Human balance during quiet stance with physiological and exoskeleton time delays

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Abstract. Human balance is studied using an inverted pendulum model, considering the effect of time delays in the muscle reflex controller and the controller of an exoskeleton. The model includes two motors at the ankle joint whose torques represent the moments generated by all plantarflexor and dorsiflexor muscles. These "muscle-like" motors obey a proportional–derivative (PD) reflex control law where the states are subject to physiological feedback delays. The exoskeleton applies torques to the ankle joint, also obeying a PD control law but with a different time delay. The stability of this system is analyzed using Galerkin projection to convert the governing neutral delay differential equation (NDDE) into a system of ordinary differential equations (ODEs); the eigenvalues of the ODE system are then computed. Stability charts demonstrate the ability of the exoskeleton to stabilize an inherently unstable biological system.

Introduction

Falling is the leading cause of injury in elderly individuals. A deeper understanding of human balance will enable the development of exoskeletons that can predict and prevent falls. Human balance has been studied using experimental techniques, but experiments are limited by the time and cost of collecting data. Many simulation-based studies of human balance during quiet stance employ a single inverted pendulum model, which has an upright equilibrium point that is inherently unstable. Ahsan et al. [1] studied inverted pendulum models of unassisted human balance, and found that proportional–derivative–acceleration (PDA) feedback generally results in larger stability margins than PD control. In this work, we investigate the stability of human balance during quiet stance when assisted by an exoskeleton at the ankle, where a PD control law is assumed for both the biological reflex controller (gains K_{pb} and K_{db}) and the exoskeleton controller (gains K_{pe} and K_{de}), and they are assumed to have different time delays (200 ms and 100 ms, respectively). Active muscle torque is assumed to depend on the angle and angular velocity of the ankle joint [2]. To study the stability of the governing NDDE, we convert it into a system of partial differential equations, then use the Galerkin approximation method to obtain a system of first-order ODEs whose behaviour approximates that of the original NDDE system. In the Galerkin method, we impose the boundary conditions using the Lagrange multiplier approach [3].

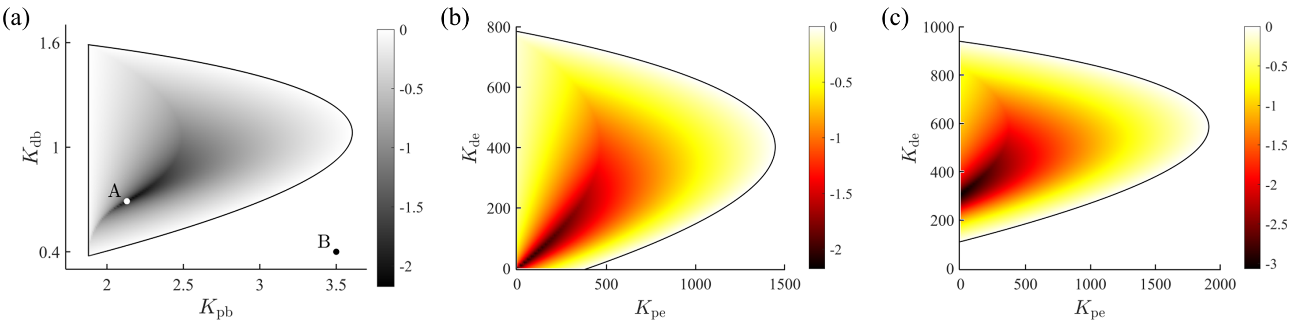

Figure 1: Stability charts of the human stance model (a) without an exoskeleton, (b) with an exoskeleton at point A ($K_{\mathrm{pb}} = 2.13$, $K_{\mathrm{db}} = 0.69$), and (c) with an exoskeleton at point B ($K_{\mathrm{pb}} = 3.5$, $K_{\mathrm{db}} = 0.4$). Colour bars indicate the location of the rightmost eigenvalue; black solid lines are the analytical stability boundaries.

Results and Discussion

The stability chart of the unassisted system is shown in Fig. 1(a), obtained using the Galerkin method and validated against the stability boundary computed analytically [4]. Point A denotes the pair of biological controller gains resulting in the most stable system; point B is one example of an inherently unstable biological system. As shown in Fig. 1(b), the stability of the system at point A can be improved by the exoskeleton, though not substantially. Note that the system is inherently stable at point A (i.e., for $K_{\mathrm{pe}} = K_{\mathrm{de}} = 0$). As shown in Fig. 1(c), the inherently unstable system at point B can be stabilized with the assistance of the exoskeleton. This simulation framework can be used to study the stability of human balance with exoskeleton assistance, considering a range of gains and time delays of the muscle reflex controller and exoskeleton controller.

References

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