Calculation of feedback delay during human balancing on rolling balance board

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Summary. Human balancing on rolling balance board in the sagittal plane is analyzed by a two-degree-of-freedom mechanical model. Human body is modeled by an inverted pendulum. The geometry of the balance board can be adjusted: the radius of the wheels and the elevation between the top of the wheel and the board can be changed. The central nervous system is modeled by a delayed proportional-derivative (PD) controller, where the constant feedback delay corresponds to the human reaction time. A critical delay can be defined for each setting of the balance board geometry: if the reaction time is larger than the critical delay, then there are no control gains that can stabilize the system. The critical time delays were determined by a numerical method for four balance board geometry with different radii. Balancing trials by a human subject were analyzed and the reaction time was estimated by comparing the theoretical and experimental results. In this particular balancing task, the reaction time was estimated to be 170 ms.

Introduction

Stabilization of the human body around an unstable equilibrium is controlled by the central nervous system (CNS). The sensory organs obtain information about the spatial position and velocity of the body and the CNS determine the corrective movement in order to maintain equilibrium. This process requires certain amount of time, therefore the balancing task can be modeled as a delayed control system, where the feedback delay is identical to the reaction time. In this study, CNS is assumed to obtain information about the angular position and angular velocity of the balance board and the human body, therefore delayed PD controller with constant time delay τ is used in the model. Nowadays, more and more accidents are caused by loss of balance during everyday activities, especially in the elderly societies. One of the main reasons of falls is the increased reaction time. Understanding the control concept and the effect of increasing feedback delay, therefore may help to predict and prevent falls.

Mechanical model

Human balancing on rolling balance board with adjustable geometry is analyzed in this work. The radius R of the wheels and the elevation h between the top of the wheel and the board can be changed, which highly influence the difficulty of balancing. Previous experiments showed that ankle strategy is dominant during balancing on rolling balance board in the sagittal plane, and oscillations at the hip are negligible compared to that at the ankle. Therefore, human body was modeled as an inverted pendulum which connects to the balance board through the ankle joint as can be seen in Fig. 1a. The control torque

$$T(t) = P_\varphi \varphi(t-\tau) + D_\varphi \dot{\varphi}(t-\tau) + P_\vartheta \vartheta(t-\tau) + D_\vartheta \dot{\vartheta}(t-\tau) \tag{1}$$

is applied at the ankle, where $P_\varphi, P_\vartheta, D_\varphi, D_\vartheta$ are the proportional and derivative control gains with respect to the generalized coordinates, which are the angle φ of the human body and angle ϑ the balance board measured from the equilibrium. Following [2], the passive stiffness s of the ankle is determined using the mass m_h and height l of the balancing subject as

$$s = 0.91 m_h g \frac{l}{2}. \tag{2}$$

The position of the ankle are described by parameter e and f as shown in Fig. 1a. The center of gravity, mass m_h and mass moment of inertia I_h of the human body were determined based on the literature [1]. The same parameters for the balance board (l_b, m_b, I_b) were calculated using the actual geometry.

Stability analysis

After deriving the governing equations of motion of the system, and linearization about the equilibrium, the mathematical model is obtained as a system of delay differential equations of the retarded type. Stability is analyzed in the four-dimensional space of the control gains $P_\varphi, P_\vartheta, D_\varphi, D_\vartheta$ for a fixed delay τ. If the value of the delay is increased, then the size of the stable domain of gains decreases and it completely disappears at a specific value, which is called critical delay ($\tau_{\rm crit}$). Stability analysis was performed over a non-uniform grid in the four-dimensional space $(P_\varphi, P_\vartheta, D_\varphi, D_\vartheta)$ such that $\pm 10\%$ inaccuracy was allowed the control gains. The critical delay was determined numerically using the Walton-Marshall method [3] above the four-dimensional grid for four different radius of the balance board ($R = 125,\ 100,\ 75,\ 50$ mm). The board elevation $R-h$ was the same in all cases, such that the board was adjusted to the lowest position of the wheel. The calculated critical delays are shown in Fig. 2. It is assumed that if the reaction time of the balancing subject is lower than the critical delay obtained based on the mechanical model, then the subject is able to stand on the balance board.

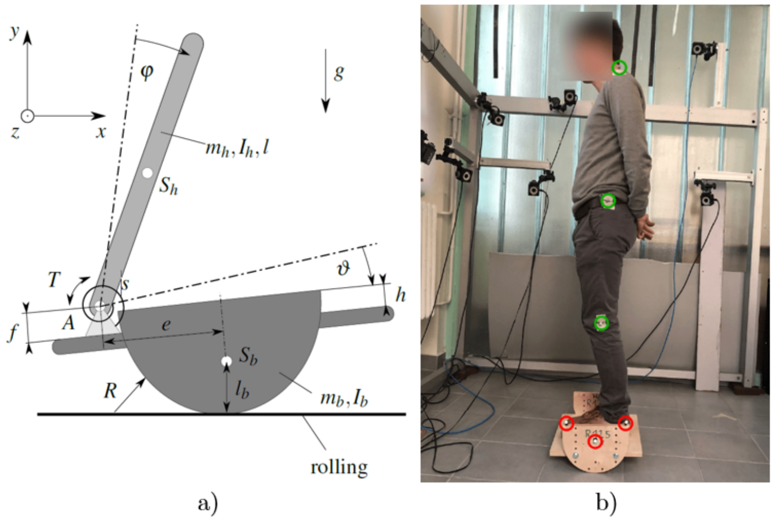

Figure 1: a) Mechanical model of human balancing on rolling balance board in the sagittal plane. b) Measurement setup.

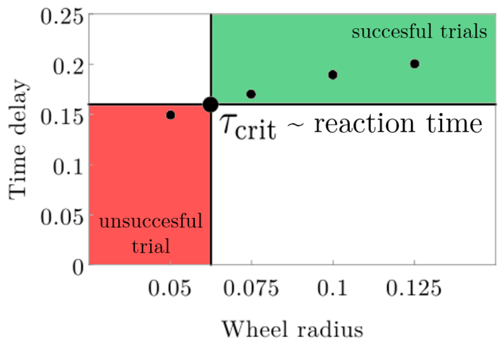

Figure 2: Estimation of reaction time based on experimental and numerical results.

Experimental analysis

The numerical results of the mechanical model were compared with actual balancing trials. A balancing subject was asked to stand on the balance board with radius 125, 100, 75, and 50 mm. The task was to stand at least 60 s long with stretched legs and open eyes. The arms had to be hold at the back as shown in Fig. 1b. Standing on the balance board with radius 125, 100, and 75 mm was successful, however, the subject was not able to stand on the balance board associated with 50 mm radius as indicated by green and red colors in Fig. 2. This means that the reaction time is between the critical delays obtained for 50 and 75 mm, which gives approximately 170 ms.

Conclusion

The reaction time can be estimated by comparing experimental and numerical results of a balancing task. The reaction time of the subject is 170 ms, which is in the range of the values that can be found in the literature [4, 5]. In the future, the calculations and experiments will be repeated involving larger number of participants.

Acknowledgment

This work was supported by the UNKP-20-3 New National Excellence Program of the Ministry for Innovation and Technology from the source of the national research, development and innovation fund.

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