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ESTIMATION OF HUMAN REACTION TIME DELAY DURING BALANCING ON BALANCE BOARD

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ABSTRACT
Human balancing on a balance board is modelled as a delayed proportional-derivative control mechanism with unknown feedback delay. The mechanical model implies that there exists a critical delay, for which no control gain parameters can stabilize the system. This theoretical critical delay is determined by numerical analysis for different geometries of the balance board. Then the results are compared to real balancing trials on balance boards with the same geometries. Comparison of the unsuccessful balancing trials to the theoretical critical delay suggests that the feedback delay of human balancing task is between 20ms and 110ms.

KEY WORDS
Balance, Gait and Locomotion. Stability. Stabilizability. Feedback delay.

1. Introduction

Mechanical modelling of human motion control is a challenging task since the parameters of the model are often uncertain and not well-defined. While dynamic parameters of the human body segments, such as mass, inertia and dimension, can be determined systematically [1], the parameters of the control algorithm employed by the nervous system during voluntary movements are more uncertain and their characterization requires more sophisticated methods. There are several concepts to describe the control mechanism of the human nervous system, such as proportional-derivative (PD) feedback [2,3,4], proportional-derivative-acceleration (PDA) feedback [5], clock- and event-driven intermittent control [6,7,8,9], act-and-wait [10], drift-and-act control [11] and predictor feedback (also called forward control) [2,5,12]. For an overall review on neuromuscular control see [13]. The common feature of the models in the above references is that goal of the control mechanism is to stabilize the system about an unstable equilibrium, such as quiet standing in the upright position or stick balancing on the fingertip.
In this paper, we analyze a special balancing task: standing on a balance board. Balancing on a balance board is a "more" difficult task than quiet standing, since the upright vertical position is "more" unstable, therefore the amplitude of the oscillations is also larger. Consequently, characteristics of human motion control are more pronounced, which can be utilized in experimental studies [14,15]. The geometry and the design of the balance board also allow one to introduce some well-defined parameters in the model and to analyze their effect on the stabilizability properties. In this paper, we investigate the effect of the radius of the arc of the balance board and the heights of the board from the ground on the stability properties.
A benchmark problem for balancing about an unstable equilibrium is the inverted pendulum subjected to a feedback mechanism. The corresponding governing equation in case of PD feedback is a second-order scalar delay-differential equation (DDE) of the form

$$\ddot{\varphi}(t) - a\varphi(t) = -P\varphi(t-\tau) - D\dot{\varphi}(t-\tau), \qquad (1)$$

where φ is the angular position of the stick, a is the system parameter, P and D are the proportional and the derivative control gains and τ is the feedback delay (reaction time). In case of a pendulum-cart model with massless cart, $a = 6g/l$ with l and g being length of the pendulum and the gravitational acceleration.
It is known that structures cannot be stabilized about their unstable equilibria via delayed PD feedback if the delay is larger than the critical value given as

$$\tau_{\mathrm{crit,PD}} = \frac{T}{\pi\sqrt{2}}, \qquad (2)$$

where T is the period of the small oscillations of the structure hung at its downward position [16]. If $\tau > \tau_{\mathrm{crit,PD}}$ then the system is not stabilizable. The scope of this paper is first to determine the critical delay for the mechanical model of balancing on a balance board, then to compare the results to the balancing abilities of human subjects by experiments. For this purpose, a balance board was manufactured with variable geometry.

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2. The balance board

The balance board and its mechanical model are shown in Figures 1 and 2, respectively. The board consist of two arcs of radius R and a board connecting them. The human subject balancing on the board is modelled as a rod of length l and mass m_h. The mass moment of inertia with respect to the axis normal to the plane of the figure through the centroid of the rod is J_h. The ankle joint is modelled as a torsional spring of stiffness k_t and a torsional dashpot of damping b_t. Following [17], the stiffness is taken to be $k_t \approx 0.8mgl/2$, i.e., it is not sufficient to keep the upright position passively stable. The damping parameter b_t. is considered to be zero during the analysis. The distance between the center of the arcs and the joint of the ankle is $h-a$. The angle of the rod (human subject) versus vertical is φ and the angle of the balance board versus horizontal is ϑ. Control action is modelled by a torque T at the ankle. In Figure 2, the torque acting on the rod from the balance board is shown. The linearized equations governing the small motions about the upright position read

$$\begin{aligned}&\left(\tfrac{1}{4}l^2m_h + J_h\right)\ddot{\varphi} + b_t\dot{\varphi} + \left(k_t - \tfrac{1}{2}glm_h\right)\varphi + \\ &\left(\tfrac{1}{2}lm_hR + \tfrac{1}{2}alm_h - \tfrac{1}{2}hlm_h\right)\ddot{\vartheta} - b_t\dot{\vartheta} - k_t\vartheta = -T,\end{aligned} \tag{3}$$

$$\begin{aligned}&\left(\frac{1}{2}lm_hR + \frac{1}{2}alm_h - \frac{1}{2}hlm_h\right)\ddot{\varphi} - b_t\dot{\varphi} - k_t\varphi \\ &\quad + \left(m_bR^2 + J_b + m_hR^2 + a^2m_h\right. \\ &\quad - 2ahm_h + h^2m_h + {l_b}^2m_b \\ &\quad \left. + 2am_hR - 2hm_hR\right)\ddot{\vartheta} + b_t\dot{\vartheta} \\ &\quad + (-agm_h + ghm_h - gl_bm_b \\ &\quad + gm_bR + k_t)\vartheta = T.\end{aligned} \tag{4}$$

Here m_b is the mass of the balance board, J_b is the mass moment of inertia with respect to the axis normal to the plane of the figure through the centroid of the balance board and l_b is the distance of the centroid of the balance board from the rolling point.

Figure 1. Balance board for balancing tests.

The control torque is assumed to be proportional to the angular positions φ and ϑ and to the angular velocities $\dot{\varphi}$ and $\dot{\vartheta}$ representing a PD controller. In order to model the reaction time of the human nervous system, a feedback delay τ is also involved into the model, thus the control torque reads

$$\begin{aligned}T = P_\varphi\varphi(t-\tau) + D_\varphi\dot{\varphi}(t-\tau) + P_\vartheta\vartheta(t-\tau) \\ + D_\vartheta\dot{\vartheta}(t-\tau),\end{aligned} \tag{5}$$

where $P_\varphi, D_\varphi, P_\vartheta, D_\vartheta$ are the proportional and the derivative control gains. Equation (3) (4) with (5) defines a DDE, whose stability properties are determined by its characteristic exponents: if the real part of all characteristic exponents is negative, then the upright equilibrium is asymptotically stable. Similarly to equation (1), there exist a critical delay τ_{crit} such that if the actual delay τ is larger than τ_{crit}, then the system cannot be stabilized by any combinations of $P_\varphi, D_\varphi, P_\vartheta, D_\vartheta$. The value of this critical delay depends on the system parameters and the board geometry including R and h.

A key point of the model is the value of the reaction time τ. Sensory information is received from different sources, such as vestibular system, visual feedback, mechanoreceptors and proprioceptors, which are all associated with different feedback delays and processing times. Still, in many models in the literature, one uniform functional feedback delay is used. Typical delay values in these models are ranging between 50ms and 200ms [7,15,18,19,20].

The primary goal of this paper is to estimate this delay through an inverse stabilizability analysis as follows. First we determine the theoretical critical delay for different combinations of the parameters R and h. Then we perform balancing tests for the same combinations of R and h. If human subjects are able to balance themselves

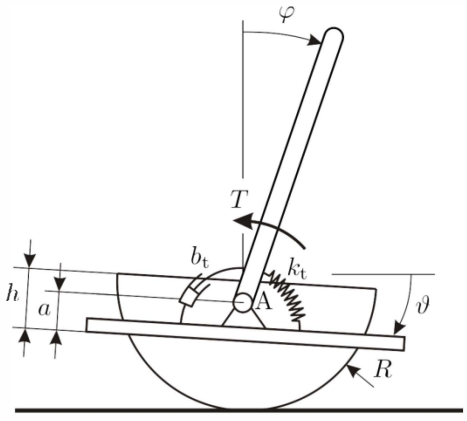

Figure 2. Mechanical modal of balancing on a balance board.

for a particular combination of R and h, then their reaction time is smaller than the corresponding theoretical critical delay. This gives a rough estimation of the human reaction delay during balancing on a balance board.

3. Theoretical stabilizability analysis

Stabilizability conditions were analyzed by employing the semidiscretization numerical technique [21] for the stability analysis of system (3) (4) with (5). First the delay was fixed to an initial value. Then, the four-dimensional parameter space $(P_\varphi, D_\varphi, P_\vartheta, D_\vartheta)$ was discretized to $10 \times 10 \times 10 \times 10$ grid points, and the stability of the system was determined numerically for each point If there was at least one parameter point associated with a stable system, then the delay was increased, and the whole procedure was performed again. The critical delay was the one for which the domain of stability in the four-dimensional space $(P_\varphi, D_\varphi, P_\vartheta, D_\vartheta)$ disappears.

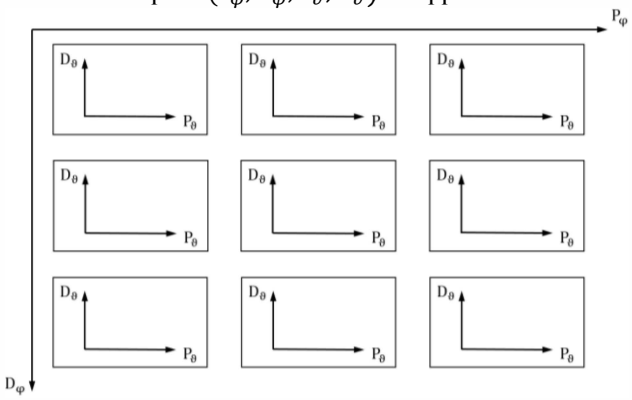

Figure 3. Structure of stability diagrams for the stabilizability analysis.

The scheme of the numerical stabilizability analysis can be represented in a 10×10 series of stability diagrams, where each diagrams corresponds to a fixed pair (P_φ, D_φ) and show the stability regions in the plane $(P_\vartheta, D_\vartheta)$ as shown in Figure 3. The stabilizability diagram is shown in Figure 5 by grayscale. For $5\text{cm} < R < 25\text{cm}$ and $2\text{cm} < h < 22\text{cm}$ the critical delay was ranging between 10ms and 350ms. Small critical delay (black shading) is achieved at small R andat large h.

4. Balancing tests

Balancing tests were performed systematically for different pairs of R and h. Six subjects were participated in the tests. The subjects were instructed to balance themselves on the balance board with their hand held to the back as shown in Figure 4. Position of the board and the subject's body was recorded using marker points. Balancing tasks were recorded by a conventional camera, and a self-made software was used to capture the position of the marker points relative to some fixed reference points. A balancing task was declared to be successful (stable balancing) if the subject was able to balance for at least 60 seconds. For successful balancing trials, the time history of the angular position ϑ of the board was used to further distinguish between balancing trials. The smaller the standard deviation of ϑ, the better the balancing performance.

Figure 5 shows the results for the 6 subjects. The results are plotted onto the theoretical estimation of the critical delay discussed in Section 3. Green circles indicate stable balancing, the size of the circles is proportional to the standard deviation of ϑ. Red circles indicate unstable balancing, when the subject was not able to balance for 60s. For one particular case (subject S2, $R = 15\text{cm}$, $h = 2\text{cm}$), the subject was able to balance for 30s, but could not reach the 60s balance time. This point is indicated by a smaller red circle.

The experimental results are in good agreement with the theoretical estimations of the critical delay. Balancing performance (standard deviation of ϑ) of all subject is better (smaller) for larger R. Parameter combination $R = 5\text{cm}$ and $h = 2\text{cm}$, which are associated with a critical delay 20ms, was unstable for all the subjects. This implies that the feedback delay for the balancing task is certainly larger than 20ms. On the other hand, parameter combination $R = 15\text{cm}$ and $h = 12\text{cm}$, which is associated with a critical delay 110ms, was stable for all the subjects. This implies that the feedback delay might be somewhere between 20ms and 110ms.

Three out of the six subjects were successful in balancing on the balance board with $R = 10\text{cm}$ and $h = 7\text{cm}$, which are associated with a critical delay 30ms. For these subjects the feedback delay might be between 20ms and 30ms. This value is in the lower range of the possible delays used in the literature [7, 15, 18, 19, 20] indicating

Figure 4. Setup for balancing tests.

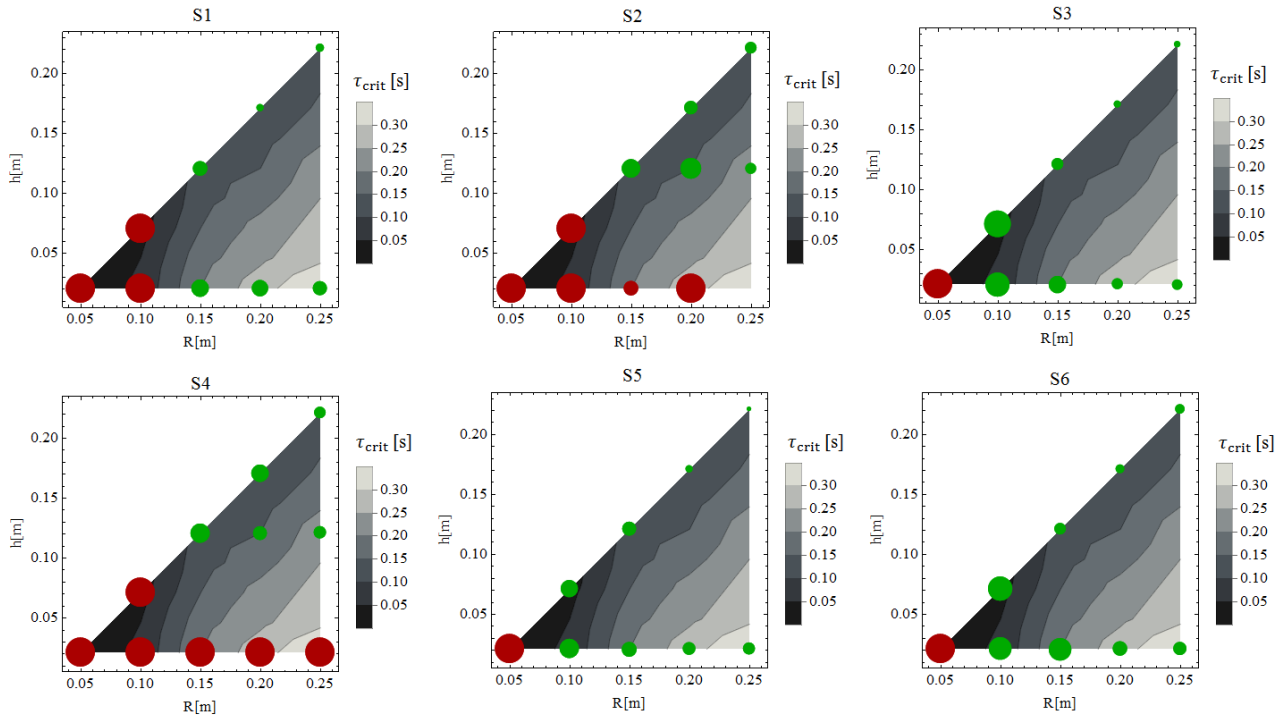

Figure 5. Stabilizability diagrams with the performance of the individual subjects. Grayscale: theoretical critical time delay; green dot: stable balancing trial; red dot: unstable balancing trial.

that the nervous system may employ some other more sophisticated control concepts to compensate for the feedback delay, such as predictor feedback [2,5,12].
It can be observed that the performance of subjects S2 and S4 was slightly worse than the other four subjects. These subjects reported previous agoraphobia and balance disorders, which explain the difference in their balancing performance.

5. Conclusion

A systematic theoretical and experimental study for the stabilizability of standing on a balance board showed that the feedback delay in the control mechanism is between 20ms and 110ms, when assuming a delayed PD feedback. For some subjects, the domain of the possible feedback delay is reduced to 20-30ms, which raised up the possibility of other than delayed state feedback, e.g., predictor feedback. In order to give a closer estimation for the feedback delay, an extended analysis will be performed involving more subjects in the balancing trials in the future.

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