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Computer simulation of human perceptual changes during balancing task on the laterally sliding stool with unstable surface

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Abstract: This paper proposes a mathematical model that explains the change of the perception, the subjective upright posture, by means of the balancing task in the seated posture on the special stool that slides laterally and rotate around the roll axis. A hypothesis on this perceptual changes is that human tends to feel an average posture during the balancing task as upright. A modeling dynamics based on this hypothesis produced the similar perceptual changes to human's.

Keywords: modeling, human behavior, balance control, motor learning, perceptual adaptation

1. INTRODUCTION

Motor control and learning mechanism has been investigated a lot in the last three decades mainly against the arm's reaching movements [1]. Among these studies, there was a report that the motor learning changed not only the motor patterns, the trajectories of the hand, but also the somatosensory perception, during the force field trainings [2].

Are such perceptual changes accompanying the motor learning only observed in the reaching movements? Based on this simple question, we started investigating the balance control [3, 4]. Behavioral measurements of human participants sitting on the specially-manufactured stool demonstrated that the subjective upright posture, the posture at which the participants do not feel their upper body inclined neither leftward nor rightward, was affected by the balancing task, during which they were asked to keep their seated posture so as to make the slowly-rotatable seat surface horizontal.

This paper aims to describe such a balancing behavior accompanying perceptual changes with a mathematical model and to explain it as dynamical system.

2. MEASUREMENT OF HUMAN BEHAVIOR

Human participants were asked to perform a balancing task at the seated posture. The experimental setup containing the stool is shown in Fig. 1. The stool was movable to the lateral direction, and its surface was rotatable around the roll axis. Using the actuator corresponding to the roll rotation, we realized 'the virtual rotation axis'. Although the roll rotation actually occurs around the mechanical rotation axis, the direction and speed of the rotation is determined by this virtual rotation axis, i.e., the spatial relation between the virtual rotation axis and the position of the center of pressure (CoP): Suppose that the CoP goes to the right of the virtual rotation axis, the stool surface does rotate to the right, even though it was actually in the left of the mechanical rotation axis.

During the balancing experiment, the virtual rotation axis was periodically shifted to the left or right. Because the participants were asked to keep the stool surface horizontal, they had to lean themselves to the left or to the right to follow their CoP to the movement of the virtual rotation axis. In the LEFT condition, the virtual rotation axis was shifted to the left during the balancing experiments, and the whole of the stool was slid to the left simultaneously in the synchronized manner.

Before and after the balancing experiments, the subjective upright posture was detected by the perceptual tests. The results of six participants on each condition were summarized in Fig. 2 [4]; (a) denotes the LEFT condition whereas (b) does the RIGHT one. The vertical direction denotes the relative position of the subjective upright posture, and its positive direction (mm) means the leaned amount to the right direction. Between the perceptual test number 1 and 2, the balancing experiment on the designated condition was conducted. On the other hand,

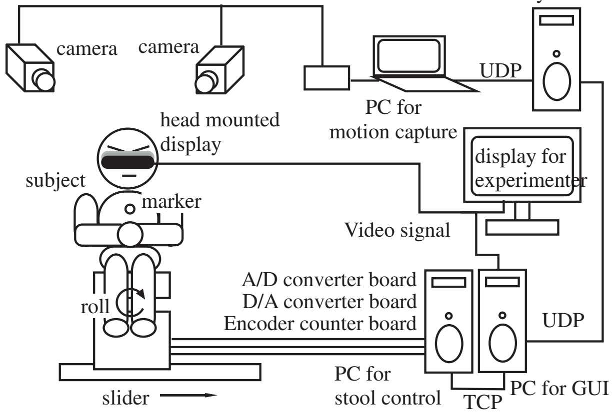

Fig. 1 Experimental setup.

† Kazuya Tomabechi is the presenter of this paper.

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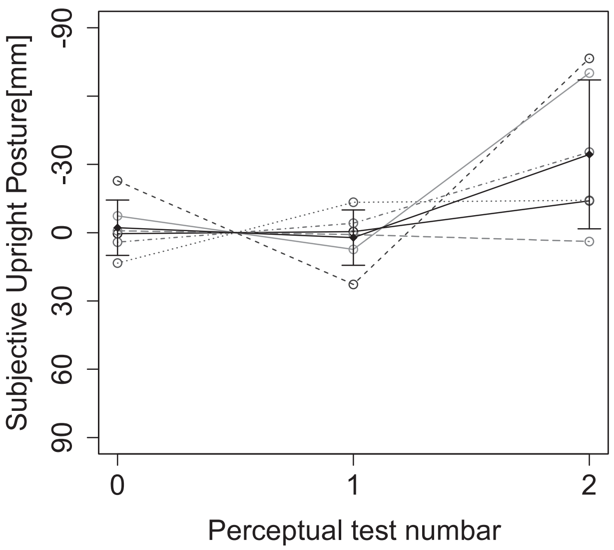
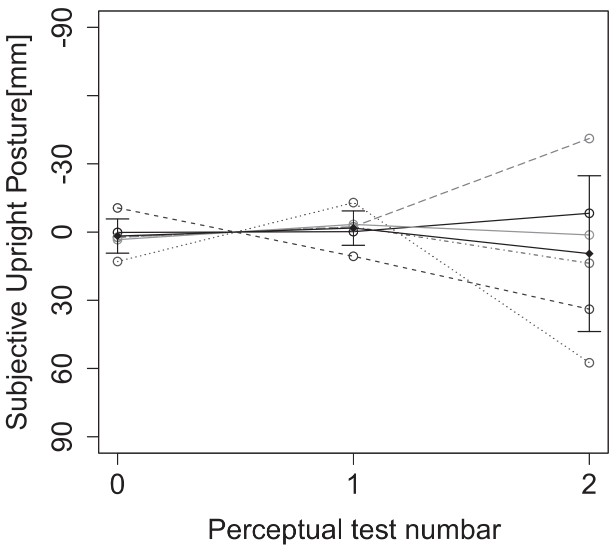


(a) LEFT condition



(b) RIGHT condition

Fig. 2 Perceptual changes.

the control experiment without seat surface rotation was introduced between the perceptual test 0 and 1.

These graphs indicate that no perceptual changes occurred during the control experiments, whereas the subjective upright posture moved to the same direction as the virtual rotation axis movement; if the participants tended to incline themselves to the left during the balance experiment, the subjective upright posture moved to the left.

3. MATHEMATICAL MODEL AND CONTROL

3.1. A link model seated on the stool surface

To Explain the phenomenon in the above, we introduced a link model as shown in Fig. 3. It comprises of the laterally sliding and rolling seat surface, the pelvis support, the first link (body) and the second link (arms, shoulders and head).

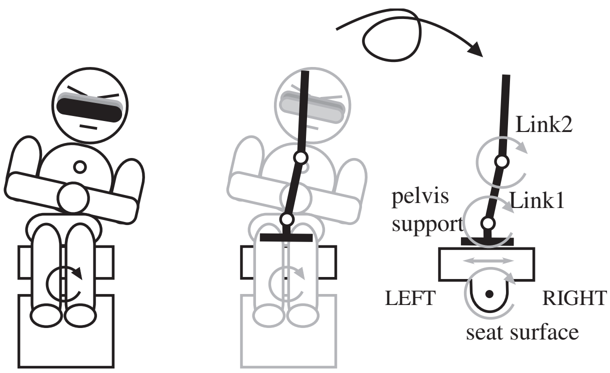


Fig. 3 A link model.

3.2. Stool motion

As the same as the human experiments [4], the slide of the whole seat as well as the shift of the virtual rotation axis were applied to the left or the right direction on each condition, respectively. The force to slide the stool F_0 and the torque of the roll rotation τ_0 was set as follows:

$$F_0 = -K_{df}\dot{x} + K_{pf}(x_{d0} - x_0) \tag{1}$$

$$\tau_0 = -K_{d0}\dot{\theta}_0 + K_{p0}(\theta_{d0} - \theta_0) \tag{2}$$

These are just PD control for their desired position x_{d0} and θ_{d0}, respectively.

The slide motion of the stool in the human experiment is a 0.4-meter left-and-right motion with 8-second period. To simulate it, we set x_{d0} as follows:

$$x_{d0} = \rho * 0.4(1 - \cos(2\pi t/8)) \tag{3}$$

where $\rho = +1$ in the RIGHT condition whereas $\rho = -1$ in the LEFT condition.

On the other hand, the definition of θ_{d0} is important to achieve the virtual rotation axis. Suppose here that the roll rotation θ_0 is always controlled to its desired position θ_{d0} thanks to the high gain feedback. In the control experiment, the seat surface was stable and thus we set

$$\theta_{d0} = 0 \tag{4}$$

to keep the seat surface horizontal. In the true experiment with the shifts of the virtual rotation axis, θ_{d0} is updated on-line depending on the distance between position of the virtual rotation axis $x_v$and the position of CoP x_{CoP}:

$$\theta_{d0} \leftarrow \theta_{d0} + k_{d0}(x_{CoP} - x_v) \cdot \Delta t \tag{5}$$

Actually, if the CoP is controlled to just above the virtual rotation axis, i.e., $x_{CoP} = x_v$, the roll rotation stop at the current position with the high gain feedback. And, if the CoP position is located to the right of the virtual rotation axis, i.e., $x_{CoP} > x_v$, then the seat will rotate to the right since θ_{d0} increases. The position of the virtual rotation axis was given as

$$x_v = -\rho\frac{0.25}{4.0}|t_p - 4.0| + 0.2 \tag{6}$$

which is the same as the human experiments. Here t_p is the time in the one period ($0 \le t_p < 8$).

3.3. Balance control

The CoP feedback control [5] was adopted to the base joint torque τ_1, while the positional control in the joint space was utilized at the upper second joint torque τ_2 to keep the body straight.

$$\begin{aligned}\tau_1 \quad &= \quad -K_{d1}\dot{\theta}_1 + K_{p1}(\theta_{d1} - \theta_1) \\ &\quad + K_{CoP}\int (x_v - P_{CoP})dt \end{aligned} \tag{7}$$

$$\tau_2 = -K_{d2}\dot{\theta}_2 + K_{p2}(\theta_{d2} - \theta_2) \tag{8}$$

where θ_1 and θ_2 are angles of the base and second joint, respectively, θ_{d1} and θ_{d2} are their desired angles which are set to zero in the simulations.

3.3.1. Perceptual adaptation

Our hypothesis for the perceptual change on the upright posture is that, subjective upright posture approaches to the posture around which the human continues to keep during the balancing tasks even though it is slanted.

The control low (7) can be rewritten as follows:

$$\tau_1 = -K_{d1}\dot{\theta}_1 + K_{p1}(\Theta_{1d} - \theta_1) \tag{9}$$

$$\Theta_{1d} = \theta_{d1} + K_{CoP}/K_{p1}\int (x_v - P_{CoP})dt \tag{10}$$

In this form, Θ_{1d} can be regarded as the desired angle for θ_1, which adaptively changes with the motion of the virtual rotation axis.

The participants might attempt to maintain the upright posture by controlling the base joint to this Θ_{1d}. Namely, we can postulate that it is possible for the participants to gradually recognize this desired posture Θ_{1d} as the upright as they usually do in the normal situation.

Now, denoting the subjective upright posture ϕ by using the angle of the base joint, its dynamics is defined as follows:

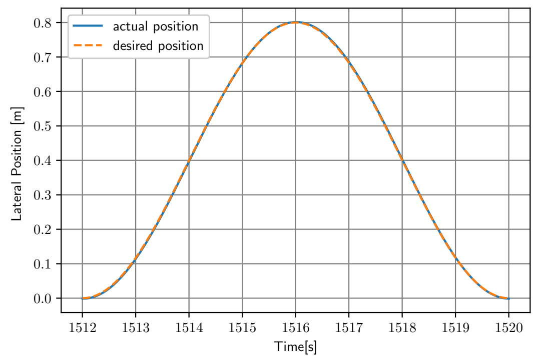
$$\dot{\phi} = k_{\phi}(LPF(\Theta_{1d}) - \phi) \tag{11}$$

Here, LPF means the filtering with low-pass property. Actually, the oscillatory component caused by x_v in (10) is unnecessary because this effect is canceled in one period: Only the stationary effect is important and this corresponds to the averaged posture in the balancing tasks.

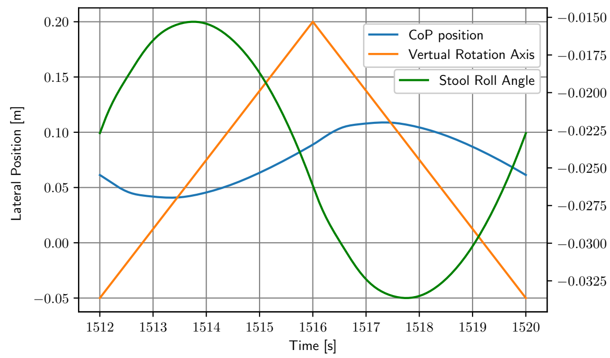
4. SIMULATIONS

4.1. Conditions

Following the model in the above section, simulations were conducted in the LEFT and RIGHT conditions. The 200 trials were simulation: the first 100 trials are the stable seat surface condition while the las 100 trails have the shift of the virtual rotation axis. The parameters are set as follows: The mass of the base, the first and the second link are 20kg, 10kg and 10kg. The moment of inertial of the base, the first and the second link are 1kg·m^2, 1kg·m^2 and 1kg·m^2. The length of the base, the first and the second link are 0.1m, 0.2m and 0.4m. The gains are $K_{df} = 300$, $K_{pf} = 500$, $K_{d0} = 50$, $K_{p0} = 500$,



(a) horizontal position



(b) rolling motion
Fig. 4 Stool motion.

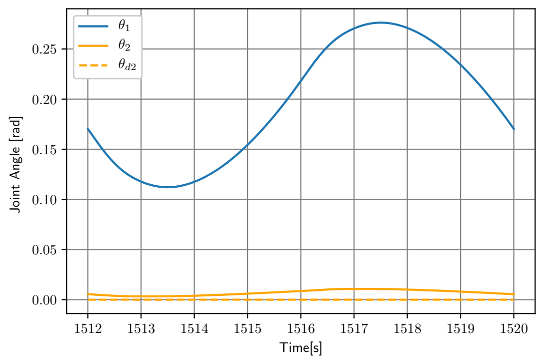


Fig. 5 Joint angles.

$K_{d1} = 50$, $K_{p1} = 500$, $K_{CoP} = 0.01$, $K_{d2} = 50$, $K_{p2} = 500$, $k_{d0} = 0.01$ and $k_{\phi} = 0.01$. The first-order system with the time constant 0.008 was used for the LPF in (11). The upright posture is set to the initial state. Python 3.7 with Open GL was used as the programing code. The 4th order Runge-Kutta method was applied to numerical integration with the step size $\Delta T = 0.001$sec.

4.2. Results

All of the results below came from the 190th trail on the RIGHT condition.

The time course of the stool motion are depicted in Fig.4: (a) shows the sliding motion (x values) with its de-

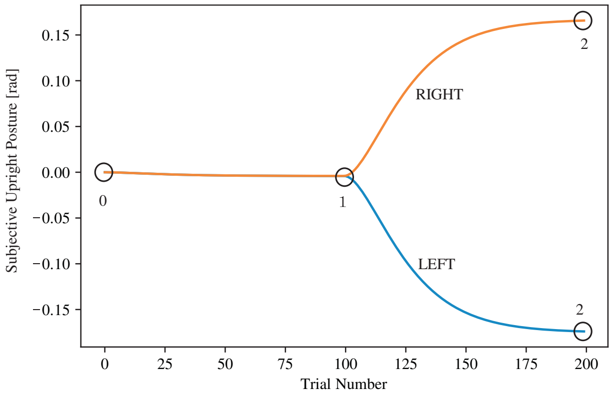


Fig. 6 Simulated perceptual changes.

sired trajectory and (b) shows the shift of the virtual rotation axis, the resultant COP position and the roll rotation angle of the stool. We confirmed that the same motion as the human experiment were replayed. Fig. 5 shows each joint angles. The balance was maintained with keeping the seat surface horizontal. In addition, the CoP was also kept within the range 0.15m at most.

Finally, the changes of the subjective upright posture trial by trial is shown in Fig. 6. Similar to the human experiments, the balancing tasks shifted the subjective upright posture to the same direction as the experimental condition, to the left or right, as shown in the last 100 trials. On the other hand, the perception was not affected in the first 100 trials where the balancing tasks were not required on the stable seat surface moving laterally.

5. CONCLUDING REMARKS

The changes of the subjective upright posture during the balancing task were simulated to mathematically explain the phenomenon observed in the human behaviors. Because the result is qualitative, quantitative explanations are required in the future works.

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