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A rule for anticipatory action planning for stepping onto two potential targets

2 つの潜在ターゲットへのステップ動作における予測的行動計画のルール

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A rule for anticipatory action planning for stepping onto two potential targets

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A rule for anticipatory action planning for stepping onto two potential targets

Dissertation by Ryo Watanabe

A thesis submitted in Fulfillment of the Requirements
for the Degree of Doctor of Philosophy

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Abstract

The brain plans an anticipatory action for performing tasks successfully and effortlessly, even if there are multiple possible options. There is increasing evidence that, when multiple actions are possible, the brain considers two factors when planning an anticipatory action: the value of the competing options and the cost of each potential action. Previous studies in which an arm-reaching task was performed while sitting suggested that the initial reaching trajectory was biased toward the option with the higher probability of occurrence or higher expected gains.

When the action involves maintaining upright balance, such as standing, stepping, or walking, the cost of maintaining postural stability could be considered predominantly. I addressed this issue by using a "go-before-you-know" task of stepping onto a target on the floor. In this task, two potential targets were located on the medial or lateral side of the stepping foot, and the true target was presented only after participants shifted their loads to leave that foot. Participants initiated their stepping actions without knowing which of the potential targets would be the true one.

I conducted four experiments (Experiments 1, 2-1, 2-2, and 3) to test the hypothesis that, when the action to be performed involves maintaining upright balance, the cost of maintaining postural stability was considered more predominantly than desirability based on the value of options. In Experiment 1, I tested this hypothesis in a situation in which the occurrence probability of each option was the same, and no gains were explicitly assigned to either option. The results showed that, for the majority of participants, lateral displacements of the center of pressure (COP) with two potential targets were similar to those when the single target existed on the medial side. Given that mediolateral postural stability became more destabilized when landing on the medial target than when landing on the lateral target, participants were likely to plan their mediolateral components of the postural adjustments to avoid postural destabilization.

In experiments 2-1, 2-2, and 3, I addressed whether the cost of maintaining postural stability continued to be considered more predominantly even when the occurrence probability of competing options (Experiments 2-1 and 2-2) or the gains from competing options (Experiment 3) were manipulated. In Experiments 2-2 and 3, both the COP displacements and the mediolateral velocity of the pelvis were measured as main outcomes to address whether the kinematic state of the body was regulated based on the same rule as with COP displacements. The results of Experiment 2-1 and 2-2 showed that, even when the lateral target was presented more frequently on the stepping side, the mediolateral COP was shifted for easy

stepping onto the medial target. These results were consistent with the findings in Experiment 1. With regard to Experiment 3, the findings obtained from the velocity of the pelvis, but not from COP displacements, showed that the body states at the lifting of the swing foot were regulated for easy stepping toward the medial target.

In summary, evidence in the current study suggests that the cost of maintaining postural stability is an important factor, in addition to the value and energetic effort, especially for planning an action that involves maintaining upright balance. In planning the preparatory posture prior to stepping movements, the cost of maintaining postural stability is a more dominant factor than relative desirability based on the value of competing options. The rule found in these experiments provides a basic framework for understanding the neural computations that occur when planning an action involving dynamic movements (i.e., walking, running, or playing sports).

CHAPTER 1: Introduction and Literature Review

An individual prepares to take a certain action by considering multiple possible options (e.g., walking while preparing for stepping on his/her left and right sides in response to the walking direction of a pedestrian coming toward him/her). Previous studies have indicated that, when planning an optimal action, the brain considers at least two factors regarding a situation—the value and the action cost of each potential option (Christopoulos and Schrater, 2015; Enachescu et al., 2021). When individuals are standing, stepping, or walking so that maintaining postural stability is a major control issue, it is possible that the cost of maintaining postural stability would be considered predominantly in planning an anticipatory action. The purpose of the present study is to investigate whether this idea is correct.

1.1. "Go-before-you-know" task: a well-known experimental task for investigating action planning

Recently, an important topic in the area of cognitive science is identifying how the brain selects an optimal action from multiple competing options. A number of studies investigating anticipatory action planning have used an arm-reaching task, in which two or more potential targets were presented simultaneously prior to initiating a reaching action, known as a "go-before-you-know" task (Gallivan et al., 2018; Wispinski et al., 2020). In a typical version of a go-before-you-know task, two potential targets are simultaneously presented at the same distance, one on each side of the hand (Fig. 1-1). Participants are instructed to initiate their reaching before knowing which target will be selected as the one to reach (the true target). Several studies have shown the trajectory tended to be an average of the two straight trajectories of both targets (Chapman et al., 2010; Stewart et al., 2014). Such a tendency has been referred to as "spatial averaging behavior." This suggests that our brain plans anticipatory actions in consideration of multiple potential options. That is, the hand used to reach a target is directed initially toward the intermediate location so that an individual could reach both targets quickly and accurately after the true one is cued.

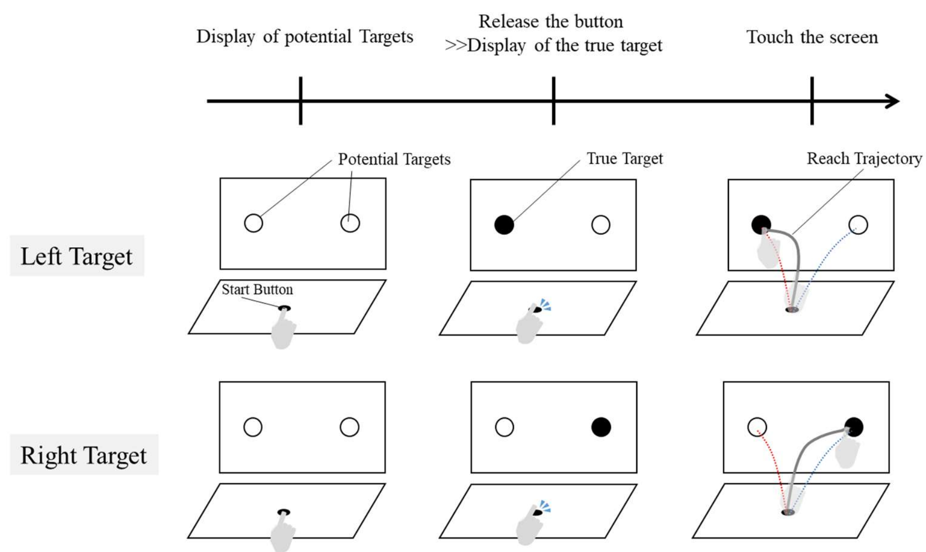

Figure 1-1. Illustration of the typical "go-before-you-know" task. Two potential targets were displayed on both the left and right sides of a touch screen. Upper or lower panels represent situations in which the left or right target was the true target, respectively. After participants released a start button, one of the potential targets was filled in black. Participants were instructed to initiate their reach quickly before knowing which target would be selected as the true target. When only a single target was displayed as a potential target, reach trajectories were aimed directly toward the cued target (red and blue lines represent typical trajectories toward the left and right target, respectively). When potential targets were displayed simultaneously, initial reach trajectories were aimed between both targets (gray lines represent typical trajectories). This figure was drawn with reference to the figures of Chapman et al. (2010) and Gallivan et al. (2011).

1.2. Action planning based on option values

A number of studies have attempted to identify the factors used for selecting an optimal action. Many studies have focused on at least two factors. The first factor considered is the value of options. The value becomes higher when the occurrence probability of a certain option is high or when the expected gain of a certain option is high. For example, when one of potential targets was selected to be the true target more frequently, the initial reaching trajectory tended to be biased toward that target

(Enachescu et al., 2021; Hudson et al., 2007). When the expected gain was higher for either one potential target or the other, initial reaching trajectories were biased toward the target with higher gains (Chapman et al., 2015). These findings suggest that the brain plans an optimal action based on the option values determined with the occurrence probability of competing options or the expected gain with success.

1.3. Action planning based on the action cost

Another factor considered is the action cost required to perform an action. Individuals plan a reaching action that is advantageous for minimizing efforts to reach toward competing targets. Previous studies used the modified version of the go-before-you-know task (Alhussein and Smith, 2021; Stewart et al., 2014). In these tasks, an obstacle, which requires more effort to avoid it and arrive at the target, was located on the path of either of two potential targets. The target located on the side with the obstacle causes increased effort because it requires avoiding an obstacle while reaching their hands directly toward the target. It is necessary to consider asymmetric efforts for planning a reaching action. Results showed that the initial trajectories were biased away from the target which is blocked by an obstacle. It is suggested that asymmetric efforts for reaching potential targets could be considered when planning the reaching action efficiently.

Considerable behavioral evidence shows that the brain considers the relative cost in physical effort required to reach one of two targets. For example, individuals preferred to reach the target requiring lower inertia of upper limbs to reach (Cos et al., 2011) or having lower resistance of external force to reach (Hagura et al., 2017). Even when either target was more highly rewarded than the other, individuals tended to select the target with lower cost but less rewards under time pressures (Pierrieau et al., 2021). These results support the contention that our brains prefer to select actions that minimize physical efforts.

1.4. Cost of maintaining postural stability

In contrast to the goal when contemplating a reaching or manipulation task while sitting, maintaining postural stability (i.e., not falling) is exclusively dominant when individuals achieve stepping movements. When stepping onto a certain spot, selecting a landing location with respect to the center of mass (COM) of the whole body is one factor that affects postural stability (Bruijn and van Dieën, 2018; Moraes, 2014). The base of support (BOS) is the area within an outline of all points formed by feet that are in contact with the ground (Bruijn and van Dieën, 2018). For ensuring upright balance within a single step, it is necessary to maintain the COM into the area of the BOS (Fig. 1-2a). Correcting the foot placement toward the medial side suddenly decreases the margin between the COM and the edge of the mediolateral BOS, causing postural destabilization (Fig. 1-2b). Previous studies have shown that mediolateral postural stability became more destabilized when placing the foot toward the medial side rather than toward the lateral side (Moraes et al., 2007; Sun et al., 2017). Therefore, it is considered that landing on the medial foot placement would have a high cost of maintaining postural stability.

Considering the cost of maintaining postural stability, individuals would not correct the stepping action that causes destabilization even if it is required to perform tasks successfully. Previous studies have demonstrated that, when individuals stand and take a single step onto the landmark in response to a sudden change of location, the magnitude of correction is less when the swing foot is corrected toward the medial side than toward the lateral side (Nonnekes et al., 2010; Reynolds and Day, 2005). Importantly, this tendency was more evident when performing a task without any balance support, such as holding handrails (Nonnekes et al., 2010; Reynolds and Day, 2005). This indicates that, to avoid a decrease in the mediolateral BOS at foot contact, individuals do not correct the foot toward the medial side much (Fig. 1-2c). These findings suggest that stepping actions are planned in consideration of the potential threat to balance when correcting the foot toward the medial side.

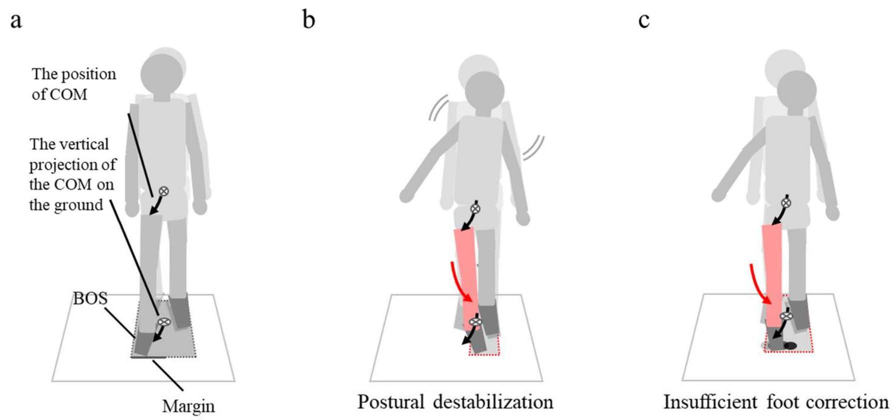

Figure 1-2. (a) Illustration of the relationship between the base of support (BOS) and the center of mass (COM). After landing on the ground, the BOS consists of both feet. When the COM falls into the BOS with sufficient margins at foot contact, COM movement is stabilized easily within a single step by applying the ground reaction force. (b) When correcting the swing foot toward the medial side, it is necessary to make the mediolateral BOS narrower. If individual intends to correct the foot sufficiently, the margin between the COM and the edge of the BOS decreases. That increases potential risks of postural destabilization (b). If individual intends to ensure postural stability, the foot correction toward the medial direction was insufficient (c).

1.5. Anticipatory postural adjustments to avoid balance disturbances

As mentioned above, it is difficult to achieve accurate foot correction while maintaining postural stability in response to a sudden change in the landing location toward the medial side. Therefore, when the possibility of foot corrections toward the medial side is assumed, it would be necessary to prepare their posture effectively to step toward the medial side. This is accomplished by anticipatory postural adjustments that precede the lifting of the stepping foot from the ground (Le Mouel and Brette, 2017). More specifically, mediolateral shifts of the center of pressure (COP) toward the swing-foot side cause decoupling of the COP and COM, causing the COM movement toward the stance leg side (Fig. 1-3). The larger the COP shift toward the swing foot side, the more the COM accelerates toward the stance foot side and the easier it becomes to step onto the medial side. Indeed, prior to stepping toward the medial side, the COP is displaced more toward the swing foot side

(Corbeil and Anaka, 2011). For that reason, the COP shift during the pre-step phase is useful for determining whether individuals intend to plan for an action to avoid upcoming postural disturbances. Even if the landing location was unknown in advance, I considered that it would be necessary for individuals to consider the possibility of foot correction toward the medial side and regulate their posture so that it is easier to step onto the medial landmark.

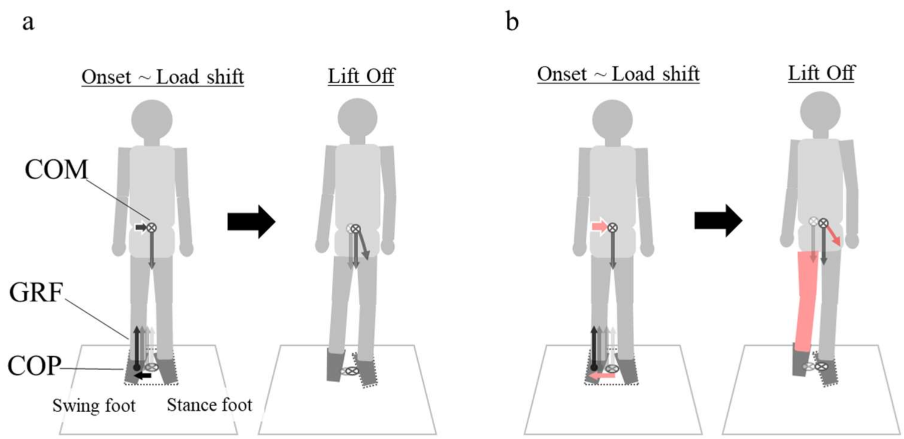

Figure 1-3. Illustration of the relationship between the base of support (BOS) and the center of mass (COM) during the pre-step phase. (a) The COP shifts toward the swing foot side, and the COP and COM decouple. This creates propulsive forces that accelerate the COM toward the stance foot side and leads to lifting the swing foot from the ground. (b) Before stepping toward the medial side, COP shifts toward the swing foot side were increased. Large propulsive forces accelerating the COM toward the stance foot side were created, making it easy to move the COM and the foot toward the medial side.

In the present study, I hypothesized that, when planning the posture for stepping onto either of two potential targets, the cost of maintaining postural stability is taken into account more than desirability based on the value of competing options. To test this hypothesis, I newly introduced the experimental paradigm of a go-before-you-know task into a stepping task. More specifically, two potential targets presented simultaneously, and participants were asked to land their foot onto either the medial or lateral landmark. The true target was selected only after participants had shifted their loads for leaving the stepping foot. Participants initiated their stepping actions without knowing which of the potential targets would be the true one. In such situations, it is hypothesized that postural adjustments would be regulated so that it is easier to step onto the landmark on the medial target, i.e., the stepping side, with a higher cost of maintaining balance.

I conducted three experiments to reveal that the cost of maintaining postural stability was considered more than desirability based on the value of competing options. In Experiment 1, one of the two potential targets became the true target with the same occurrence frequency (i.e., 50% probability for both targets). I tested the hypothesis that, when the probability of occurrence is the same for the two potential targets, preparatory postural adjustments would be made so that it is effective to step toward the medial side rather than toward the lateral side.

In Experiments 2-1 and 2-2, the lateral target became the true target more frequently (80% probability). If the occurrence probability was considered as in the reaching task (Enachescu et al., 2021), then preparatory postural adjustments would be made so that it is effective to step onto the lateral target. In contrast, if the cost of maintaining postural stability is considered more dominantly, then preparatory postural adjustments for easy stepping onto the medial target would be observed. Experiment 2-2 was conducted to replicate the findings of Experiment 2-1 after solving technical issues that could limit the conclusions of Experiment 2-1.

In Experiment 3, the gain was assigned to two potential targets, and the lateral target was assigned a higher value than the medial target. If the gain of option is predominantly considered for planning the posture (Chapman et al., 2015), then preparatory postural adjustments would be made so that it is effective to step onto the lateral target. In contrast, if the cost of maintaining postural stability is considered more predominantly, then preparatory postural adjustments to step effectively onto the medial target would be observed.

Throughout four experiments, I investigated whether the cost of maintaining postural stability was considered more predominantly than the value of competing potential options for planning an anticipatory action that involves maintaining upright balance (See also Table 1).

	Factor	Medial	Lateral
Experiment 1	Costs for maintaining postural instability	**High**	Low
	Occurrence Probability	Even	Even
	Gain	-	-
Experiment 2-1 Experiment 2-2	Costs for maintaining postural instability	**High**	Low
	Occurrence Probability	Low	**High**
	Gain	-	-
Experiment 3	Costs for maintaining postural instability	**High**	Low
	Occurrence Probability	Even	Even
	Gain	Low	**High**

Table 1. A Summary of factors influencing the cost and value of options

CHAPTER 2: Experiment 1

2.1. Purpose

The purpose of Experiment 1 was to address whether, when the probability of occurrence is the same for the two potential targets, preparatory postural adjustments would be made so that it is effective to step toward the medial side. The cost of maintaining postural stability would be higher at landing on the target located on the individual's medial side than the individual's lateral side. If these costs are taken into account for planning postural adjustments, then the magnitudes of the lateral COP displacements would be scaled similar to those when a single stepping target is on the individual's medial side.

2.2. Material and Methods

2.2.1. Participants

Fourteen young individuals (six females) participated in this experiment. All participants were right-leg dominant and had not reported any history of musculoskeletal or neurological disorders in their self-reports. This experiment was approved by the Ethics Committee of Tokyo Metropolitan University (approval number: H2-65). All participants provided written informed consent and received a bookstore gift card for their participation. The data obtained from one participant was excluded from the following analysis due to system failure. I used data obtained from thirteen participants for the following analysis procedure (age: 23.0 ± 3.4 years; height: 164.3 ± 11.3 cm; weight: 60.0 ± 10.2 kg).

2.2.2. Apparatus

The experimental setup is shown in Figure 1. It consisted of two computers for data measurement and stimulus presentation, a 27-inch LCD monitor with 60 Hz (LCD-MF276XD, I/O DATA, Japan), 14 cameras for three-dimensional motion capture (Oqus300SYS, Qualisys, Sweden), two force plates (Kistler 9286AA type and 9286BA type, Kistler, Switzerland), an analog board (64-channel analog interface, Qualisys, Sweden), and a D/A converter (MMB Trigger Box, Neurospec, Switzerland). Fourteen passive retro-reflective markers were attached to seven anatomical landmarks of each participant's lower body bilaterally (second toe top, first metatarsal, second metatarsal, fifth metatarsal, heel, anterior superior iliac spine, and posterior superior iliac spine). Spatial locations of markers were tracked with three-dimensional motion cameras at a sampling frequency of 100 Hz and processed with the motion capture software (Qualisys Track Manager, QTM; Qualisys, Sweden). The ground reaction forces and COP were measured with the two force plates at a sampling frequency of 1000 Hz. These data were recorded with the QTM through a 64-channel analog board. Software (TRIAS2, Q'sfix, Japan) was used to control a charge amplifier of both force plates and initialize the states of plates before each trial started.

Visual and auditory stimuli were generated using PsychoPy3 (Peirce et al., 2019). All visual stimuli were displayed on the monitor. Temporal information about stimulus generation was sent to the QTM as analog signals through a D/A converter (MMB Trigger Box, Neurospec, Switzerland). To calculate a participant's load shift in real time and display visual stimuli with his/her movements, the force data were sent from the QTM in real-time to a customized Python program (Qualisys Python SDK, Qualisys, Sweden), and the differences between vertical forces acquired from both force plates were compared using the measurement computer. The measurement computer was connected to the stimulus-presentation computer with a RS-232C cable. A signal was sent from the measurement computer to the stimulus-presentation computer to change the visual stimuli when the difference between both vertical forces exceeded the setting values (10% of total body weight). There were processing several delays from the sending of the signal to the changing of the visual stimuli on the monitor. Preliminary measurement using a high-speed camera sampling frequency of 240 Hz showed that the delay was estimated to be about 217 ms.

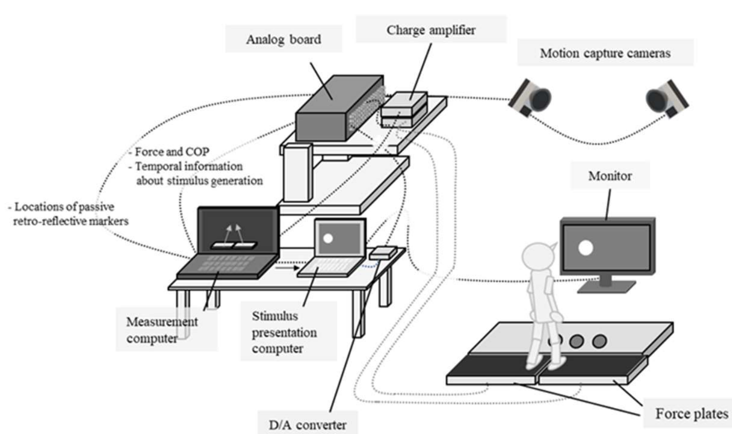

Figure 2-1. Experimental setup.

2.2.3. Task and protocol

The task setup is shown in Figure 2. Three landmarks, which was used as stepping targets, were located on an ethylene-vinyl acetate mat 32.5 cm in front of the participant's toe position (Fig. 2a). The central landmark was located ahead of the right foot (i.e., the swing foot), whereas the lateral and medial landmarks were located 10 cm away from the center landmark. The monitor was located on the floor about 112.5 cm in front of the participant.

Participants stood barefoot on the dual force plates. They were instructed to adjust their toes and heels to correspond with tapes on each force plate so that, at the start of each trial, the distance between their heels was maintained at 20 cm, and the anterior–posterior distance between the target and the toe of right foot was 32.5 cm. Participants also tried to distribute their loads evenly between both feet.

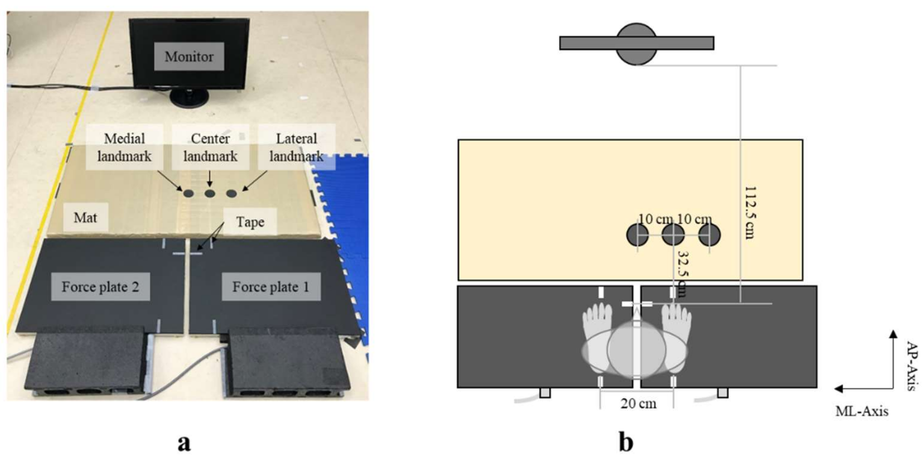

Figure 2-2. Task setup: (a) a picture of the task setup; (b) top view of the configuration of the task setup

Each trial started with a plus-shaped fixation point presented on the center of the monitor for 1000 ms. As soon as the fixation point disappeared, the first auditory beep was presented concurrently with either one or two circles shown on the monitor. In the single-target condition (Fig. 3a), a single circle appeared on either the center, right, or left side of the monitor with the first auditory beep. The position of the circle (center, right, and left) represented the direction of stepping target (center, lateral, and medial targets). After a random interval (1000–1500 ms) after the target's appearance, a secondary auditory beep cued participants to step onto the floor landmark (i.e., the stepping target) corresponding to the circle presented on the monitor (see Fig. 3a). There was no time limit for generating an action after a go signal. However, participants were instructed that they should try to step quickly and accurately on the specified landmark so that the marker attached to their second metatarsal bone head of the swing foot would align vertically with the center of the floor landmark. In the dual-target condition (Fig. 3b), both right and left circles were presented simultaneously (i.e., the lateral target and the medial target, respectively). After a random interval (1000–1500 ms), a second auditory beep cued participants to start moving while they did not know which was the correct target. The true target was displayed, while the other potential target disappeared when the difference in vertical force between the right- and left-foot sides exceeded 10% of the total body weight. The threshold value of 10% was determined based on the pilot study. It was ideal to present the true target as soon as the peak of the lateral displacements of the COP on the swing side occurred (i.e., it was presented at the timing between the unloading and early swing phase). If the true target was presented much earlier than that, participants could adjust their load shifts corresponding to the location of the true target. Because there was a mechanical delay of about 217 ms from the sending of the signal to the changing of the visual stimuli on the monitor, I needed to explore the timing to reliably present the true target after the peak of the lateral displacement of the COP. In the pilot study, I decided that setting the threshold value at 10% of the total body weight was reasonable for dealing with the issue.

Trials in which participants loaded unevenly on either the right or left foot over threshold values at the moment of the second auditory beep were regarded as invalid and were not included in the main trials. In such trials, either "R OVER" or "L OVER" was displayed on the monitor just after the secondary auditory beep to ask participants to avoid standing unevenly.

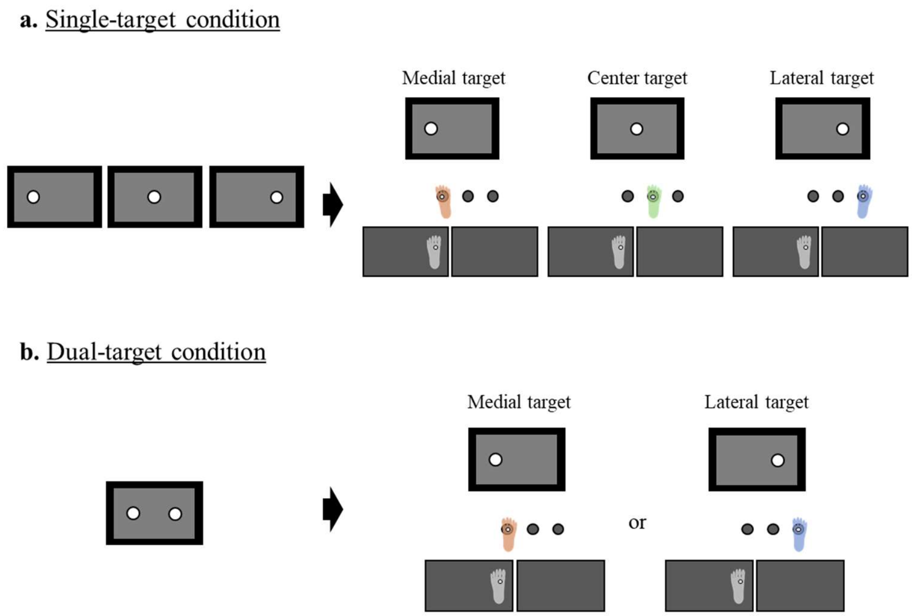

Figure 2-3. Illustration of trial types: (a) single-target condition; (b) dual-target condition

Participants performed a total of 240 main trials. Trials were divided into sets of 120 trials per day to avoid fatigue. Each day, participants performed the task for 72 trials under the single-target condition and 48 dual-target trials under the dual-target condition. Under the single-target condition, each of the center, right, and left targets appeared for 24 trials. Under the dual-target condition, each of the right and left targets was selected as the true target for 24 trials. Trials regarded as invalid for uneven loads were subtracted from the trials of each condition. The trial order of the single-target trials and dual-target trials was randomly intermixed, which is the same as in the previous study (Wong and Haith, 2017). To avoid fatigue, participants rested in every 30 trials. All participants completed each day's tasks within three hours.

To familiarize participants with the task, they performed 20 training trials on both days before the main trials. In this session, participants first completed 10 trials in which two trials for all target conditions of both single-target trials and dual-target trials were performed in the following order sequentially: single-center, single-lateral, single-medial, dual-lateral, and dual-medial. Participants completed 10 trials, in which two trials for each target condition were presented in randomized order.

2.2.4. Data analyses

Before data processing, all force plate data and all marker data were offline low-pass filtered at 20 Hz and 4 Hz, respectively (fourth-order Butterworth). The global COP position was calculated from the output of both force plates according to the following equation (Honeine et al., 2016):

$$\mathrm{COP}_{global} = [(\mathrm{Fz}_1 * \mathrm{COP}_1) + (\mathrm{Fz}_2 * \mathrm{COP}_2)] / (\mathrm{Fz}_1 + \mathrm{Fz}_2),$$

where Fz_1 and Fz_2 are the vertical ground reaction forces on the left- and right-foot sides, respectively, and COP_1 and COP_2 are the COP positions on the left- and right-foot sides, respectively. The coordination system of COP_1, COP_2, and global COP were based on the global coordinate system. The velocity of global COP was calculated by time derivatives using the three-order central difference method.

The onset of the lateral COP shift was determined as the first point at which the medial-lateral velocity of the global COP toward either foot side exceeded 0.05 m/s and then continued for at least 50 ms (Bancroft & Day, 2016). The lateral peak point of the COP movement was defined as the mediolateral peak of the COP movement toward the swing (right) foot, as established in the previous study (Corbeil and Anaka, 2011; MacKinnon et al., 2007). Notably, multiple peaks of COP movements were observed in some trials. Considering this issue, and to avoid contamination of feedback adjustments in response to the true target presentation, I defined the initial peak of these COP patterns as the lateral peak point of the COM movement. The lateral displacement of the COP toward the swing foot was defined as the lateral movement distance of the COP from the position at the onset of the COP movements to the position at the initial lateral peak of the COP movements (Corbeil and Anaka, 2011). To evaluate dynamic postural stabilities when landing the swing foot on a target, the margin of stability (MOS) at foot contact was calculated. The MOS was defined as the distance between the boundary of the BOS and the extrapolated COM (XCOM) at foot contact. Foot contact was determined as the first point at which the vertical velocity of the second metatarsal marker exceeded -0.02 m/s from the minimum point. I calculated the MOS by using pelvis markers and foot markers following the definition of Sun et al. (2017). The location of the COM was estimated from the average position of the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) markers. The XCOM was calculated according to the following equation (Hof et al., 2005):

$$XCOM = COM + v/\sqrt{g/L},$$

where v is the COM velocity, g is the gravitational acceleration (9.81 m/s^2), and L is the vertical distance between the COM and the average position of the right and left heel marker during quiet stance. The MOS in the anteroposterior direction (MOS_{AP}) was defined as the distance between the toe marker of the swing foot and the XCOM. The MOS in the mediolateral direction (MOS_{ML}) was defined as the distance between the fifth metatarsal marker of the swing foot and the XCOM. These analyses were performed using a customized program in MATLAB (MATLAB ver. R2020a, MathWorks, USA).

2.2.5. Statistical analyses

Before statistical analysis, I excluded the following trials: (1) between the first auditory sound and the second auditory sound, participants stood with their weight uneven (over 55% of their weight on either side); (2) the onset of the COP movement was detected before the second auditory sound; (3) the COP shifted initially toward the stance limb side and/or the forward direction just after the onset of the COP, which meant an abnormal COP pattern; (4) the true target was presented before the initial lateral peak of the COP displacements. I realized that there was little valid data in the dual-target condition of ID2 as compared with that of other participants. I checked whether including or excluding data of ID2 participant affected the following statistical procedures. The results showed that the rejection of null hypotheses in statistical analyses remained unchanged, regardless of whether the data of ID2 was included or not. Therefore, I included the data of ID2 to avoid a smaller sample size.

The main dependent variable was the lateral displacement of the COP toward the swing limb, MOS_{AP}, and MOS_{ML}. For this variable, a two-way (number of targets and stepping side) analysis of variance (ANOVA) with repeated measures on both factors were used to statistically analyze the dependent variable. The threshold of significance was set at $p < 0.05$. Effect sizes are reported as partial η^2 (η_p^2) statistics for the relevant main and interaction effects. Greenhouse-Geisser corrections were applied to the degrees of freedom if violations of the assumption of sphericity were detected in Mendoza's Multisample Sphericity Test. Statical procedures of ANOVA were performed using the anovakun function (ver. 4.8.5) in R (ver. 4.1.0).

I also performed Bayesian modeling to reveal the individual weight between the policies of medial stepping and lateral stepping. Specifically, I used a Bayesian model to estimate the parameters: weighting values $w_{(k)}$ and the standard deviation,$\sigma_{(k)}$, which were fitted to each participant (k). In detail, I set the model structure as follows:

$$\bar{\mu}_{D(k)} = w_{(k)} * \bar{\mu}_{sm(k)} + \left(1 - w_{(k)}\right) * \bar{\mu}_{sl(k)}$$
$$Y_{(\mathrm{k},\ i)} \sim \mathrm{Normal}\left(\bar{\mu}_{\mathrm{D(k)}}, \sigma_{(k)}\right),$$

where $\bar{\mu}_{SM(k)}$ and $\bar{\mu}_{SL(k)}$ are the average values for each participant acquired from the lateral stepping and the medial stepping under the single-target condition, respectively. $\bar{\mu}_{D(k)}$ is the weighted average under both $\bar{\mu}_{sm(k)}$ and $\bar{\mu}_{sl(k)}$, which are weighted with the parameter $w_{(\mathrm{k})}$. $w_{(\mathrm{k})}$ means weighted values that produces the value of mean bounded to the upper and lower saturation values. The lower and upper value is the mean of the single-lateral and single-medial condition, respectively. Therefore, $w_{(\mathrm{k})}$ represents the individual weight between the policies of medial stepping and lateral stepping. $\sigma_{(k)}$ represents the standard deviation of the Gaussian distribution of average $\bar{\mu}_{\mathrm{D(k)}}$. We fitted the Gaussian function with the mean $\bar{\mu}_{D(k)}$ and standard deviation $\sigma_{(k)}$ to the data of lateral displacements of the COP pooled over both the lateral-lateral and the dual-medial conditions $Y_{(k,\ i)}$. Regarding the individual weight $w_{(k)}$, the prior parameters were modeled using a uniform distribution (lower = 0, upper = 1). At parameters $\sigma_{(k)}$, I specified the prior parameters using a uniform distribution (lower = 0, upper = 1000). A uniform distribution was selected for having an equal probability among theoretically possible values. Posteriors were calculated using Markov chain Monte Carlo sampling based on the Hamiltonian Monte Carlo method. The sampling method was based on the No-U-Turn Sampler (NUTS) algorithm. I produced four chains with 25,000 samples. Simulations were preceded by 5000 burn-in steps, which were excluded due to collecting samples from a stationary distribution, and the remaining 20,000 were used for each parameter estimation. Convergence checking was executed based on R-hat diagnostic values. R-hat diagnostic values were below 1.1 among all parameters. All procedures of the Bayesian modeling and output of results were performed using Rtools (ver. 4.0) and the RStan package (ver. 2.21.2) in R (ver. 4.1.0).

2.3. Results

Comparing the magnitudes of the lateral displacements of the COP toward the swing leg between the single- and dual-target conditions

Mean lateral displacements of the COP toward the swing-foot side is shown in Figure 2-4. A two-way ANOVA showed significant main effects of the number of targets ($F_{(1, 12)} = 26.33$, $p < .001$, $\eta_p^2 = 0.69$) and the stepping side ($F_{(1, 12)} = 32.66$, $p < .001$, $\eta_p^2 = 0.73$). Lateral displacements of the COP were greater under the dual-target condition than those under the single-target condition. Regarding the main effect of stepping sides, lateral displacements of the COP were greater under the medial condition than those under the lateral condition. The interaction was also significant ($F_{(1, 12)} = 71.62$, $p < .001$, $\eta_p^2 = 0.86$). Simple main effects of the interaction between two factors revealed that lateral displacements of the COP were greater under the dual-lateral condition than those under the single-lateral condition ($F_{(1, 12)} = 60.16$, $p < .001$, $\eta_p^2 = 0.83$). In addition, lateral displacements of the COP under the single-lateral condition were greater than those under the single-medial condition ($F_{(1, 12)} = 69.01$, $p < .001$, $\eta_p^2 = 0.85$). There was no significant difference between the single-medial condition and the dual-medial condition ($F_{(1, 12)} = 2.95$, $p = .112$, $\eta_p^2 = 0.20$). There was also no significant difference between the dual-medial target condition and the dual-lateral target condition ($F_{(1, 12)} < 1.0$, $p = .598$, $\eta_p^2 = 0.02$).

In summary, a significant interaction showed that lateral displacements of the COP under the dual-target condition were greater than those of stepping toward the lateral side under the single-target condition and comparable with those of stepping toward the medial side under the single-target condition.

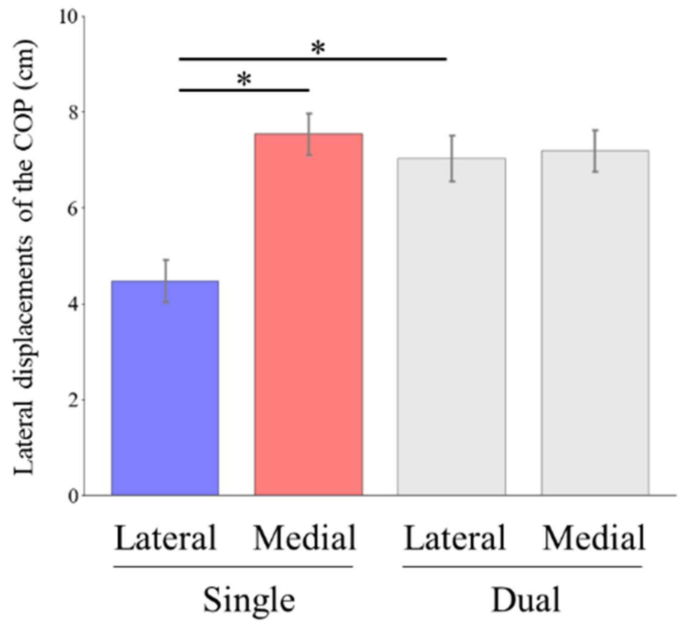

Figure 2-4. Mean lateral displacements of the COP toward the swing-foot side. A blue bar represents a mean under the single-lateral condition. A red bar represents a mean under the single-medial condition. Light gray bars represent means under the dual-target condition. Error bars represent standard errors of the mean under each condtition. An asterisk (*) indicates a significant difference in group means based on post hoc analysis ($p < .05$).

Individual weight between the policies of medial stepping and lateral stepping

Estimated weight values for each participant are shown in Figure 2-5. The posterior mean was greater than 0.67, which represents a medial weighting pattern, in the ten of 13 participants. Posterior means were around 0.5, which represents an intermediate weighting pattern, were observed in only three of 13 participants.

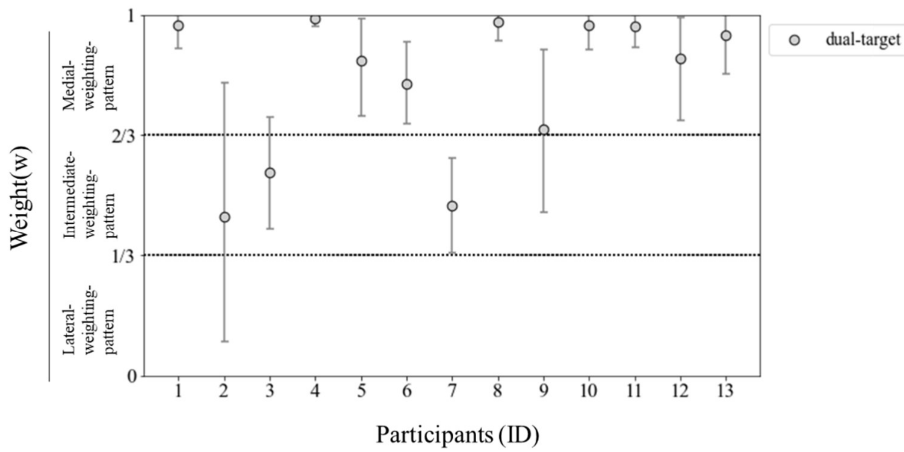

Figure 2-5. Estimated individual weight values between the policies of medial stepping and lateral stepping under the dual-target condition. Dots represent a posterior mean of the weight values for each participant. Error bars represent a 95% creditable interval of each estimated value. Each value of weight was categorized in one of three patterns: medial-weighting (the values greater than 0.67), intermediate-weighting (0.33-0.67), and lateral-weighting (smaller than 0.33).

Anteroposterior and Mediolateral Margin of stability at foot contact

Regarding the MOS_{AP} (Fig. 2-6a), a two-way ANOVA showed that only interactions were significant ($F_{(1, 12)} = 17.43$, $p = .001$, $\eta_p^2 = 0.59$). Simple main effects of the interaction between two factors revealed that the MOS_{AP} under the single-medial condition was larger than that under the single-lateral condition ($F_{(1, 12)} = 12.28$, $p = .004$, $\eta_p^2 = 0.51$). Additionally, the MOS_{AP} under the dual-lateral condition was larger than that under the single-lateral condition ($F_{(1, 12)} = 7.70$, $p = .017$, $\eta_p^2 = 0.39$). Regarding the dual-target condition, the MOS_{AP} under the lateral stepping condition was larger than that under the medial stepping condition, but the difference failed to reach statistical significance ($F_{(1, 12)} = 4.51$, $p = .055$). There were no other significant effects. In summary, the MOS_{AP} was not reduced when taking a step onto a target under the dual-target condition.

Regarding the MOS_{ML} (Fig. 2-6b), a two-way ANOVA showed a significant main effect of the stepping side ($F_{(1, 12)} = 165.46$, $p < .001$, $\eta_p^2 = 0.93$). The interaction was also significant ($F_{(1, 12)} = 6.43$, $p = .026$, $\eta_p^2 = 0.35$). Simple main effects of the interaction between two factors revealed that the mediolateral MOS reduction under the single-medial condition was more significant than that under the single-lateral condition ($F_{(1, 12)} = 144.75$, $p < .001$, $\eta_p^2 = 0.92$). Additionally, the MOS_{ML} reduction under the dual-medial condition was also more significant than that under the dual-lateral condition ($F_{(1, 12)} = 99.28$, $p < .001$, $\eta_p^2 = 0.89$). Regarding the lateral stepping condition, the MOS_{ML} under the dual-target condition was larger than that under the single target condition, but the difference failed to reach statistical significance ($F_{(1, 12)} = 4.48$, $p = .056$).There were no other significant effects. In summary, stepping on the medial target led to a greater reduction in the MOS_{ML} than did stepping on the lateral target.

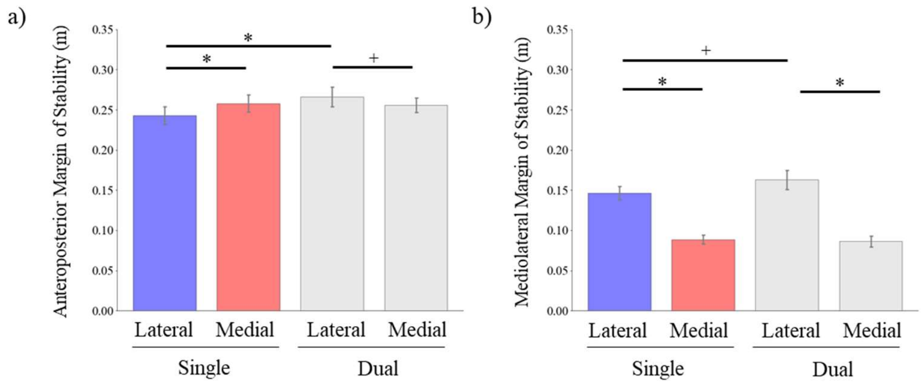

Figure 2-6. Mean values of the MOS_{AP} (a) and the MOS_{ML} (b) at foot contact. A blue bar represents average values in the single-lateral condition. A red bar represents a mean in the single-medial condition. Light gray bars represent means in the dual-target condition. Error bars represent standard errors of the mean. An asterisk (*) indicates a significant difference in group means based on a post hoc analysis ($p < .05$). A plus sign (+) indicates a marginally significant difference in group means based on post hoc analysis ($p < .10$).

2.4. Discussion

As hypothesized, lateral displacements of the COP with two potential targets were similar to those when a single target existed on the individual's medial side. Bayesian estimations of individual strategies also showed that medial weighting patterns of the COP were more dominant than intermediate weighting patterns among participants. These results suggest that, when an action involves maintaining upright balance, the cost of maintaining postural stability is likely to be considered dominantly for planning postural adjustments.

The results of the lateral COP displacements indicated that the mediolateral components of posture adjustments during the pre-step phase were regulated for easy stepping onto the medial target. In consideration of another result that the MOS_{ML} became more destabilized when stepping onto the medial target than when stepping onto the lateral target, these postural adjustments may reflect the compensatory strategy to avoid balance disturbances in the mediolateral direction. A similar strategy was reported in other actions performed while standing (Aimola et al., 2011; Xie & Wang, 2019). When there were three objects with different weights and individuals were about to lift one of the objects without knowing the object's weight, the COP displacements were comparable with those when lifting the heaviest object when instructed about its weight (Aimola et al., 2011). When catching one of three objects with different weights, the COP displacements before catching the object of unknown weight were comparable with those before catching the heaviest object (Xie & Wang, 2019). These postural adjustments have been considered to be planning based on the maximum assumption of perturbation magnitudes when the weight of an object was uncertain (Eckerle et al., 2012; Xie & Wang, 2019). In line with these studies, the present findings suggest that the brain selects a medial weighting pattern as a predictive compensation based on the cost of maintaining postural stability to avoid potential perturbations of balance when stepping onto competing potential targets.

For three of 13 participants, lateral displacements of the COP were scaled at intermediate locations between those for stepping onto medial or lateral targets. As a reason why the intermediate weighting pattern was selected in the present task, the potential threat to balance disturbances might be less high even when rapid adjustment of the swing foot medially occurred. In the current task settings, the lateral and medial targets were located 10 cm apart from the center target position. Balance disturbances from stepping onto a medial target may have not been sufficient to cause the potential threat to balance disturbances. Participants may have considered that they would be able to correct the swing foot toward the medial side without destabilization, even with displacing the COP at an intermediate location. For that reason, tolerances for potential perturbations of balance in accordance with the possible options might affect which strategy is used in the brain, as suggested in previous studies using an object-lifting task (Brooks & Thaler, 2017; Cashaback et al., 2017).

Based on the findings of Experiment 1, I tentatively conclude that postural adjustments for stepping onto two competing targets would be planned based on the cost of maintaining postural stability at least when relative values of competing potential targets were the same. In the following experiments, I addressed whether this would be the case even when a potential target with the higher cost for maintaining postural stability became the true target less frequently (20% frequency, in Experiments 2-1 and 2-2), and when the gain (i.e., the reward) was lower for the potential target with the higher cost for maintaining postural stability (in Experiment 3).

CHAPTER 3: Experiment 2-1

3.1. Purpose

The purpose of the Experiment 2-1 was to address whether action planning that involves maintaining an upright posture was affected more dominantly by the cost of maintaining postural stability than by the occurrence probability of competing options. For this purpose, trials under the dual-target condition, which were the same as those used in Experiment 1, were performed under an unequal-probability condition (medial : lateral = 0.2 : 0.8) as well as under an equal-probability condition (i.e., the same as in Experiment 1). If the cost of maintaining postural stability was dominant in action planning, then lateral displacements of the COP with two potential targets would be similar to those when stepping onto the target located on the individual's medial side, irrespective of the occurrence probability.

In Experiment 2-1, I also checked the timing of lifting the foot off the ground after displaying the true target under the dual-target condition. This was necessary to verify whether the time of the foot lift from the display of the true target was similar among participants.

3.2. Materials and methods

3.2.1. Participants

Ten young individuals were recruited (four males and six females, age: 22.0 ± 2.9 years; height: 162.5 ± 11.3 cm; weight: 58.2 ± 9.8 kg). The Procedures and criteria of participation were same as in Experiment 1. This experiment was approved by the Ethics Committee of Tokyo Metropolitan University (approval number: H4-88).

3.2.2. Apparatus

The same apparatus as in Experiment 1 was used, except that the methods for streaming the data were changed. In Experiment 1, QTM and Psychopy ran on two computers separately and connected with RS232. There were delays of about 217 ms from the sending of the signal to the changing of the visual stimuli on the monitor. In Experiment 2-1, both QTM and Psychopy were run simultaneously on a single computer with local network communication. As a result, the delay was improved to be about 48 ms. Next, the threshold values were altered to display the visual stimuli. Accordingly, the threshold value for displaying the true target was modified so that the timing of displaying the true target was similar to that in Experiment 1.

3.2.3. Task and procedure

The same task as in Experiment 1 was used, except for changing the occurrence probability of each option under the dual-target condition and excluding the trials of stepping onto the center target under the single-target condition. With regard to the occurrence probability setting of two potential targets under the dual-target condition, I followed the setting in a recent study using an arm-reaching task (Enachescu et al., 2021). There were two conditions that differed in the probability of occurrence frequency: the equal-probability and unequal-probability conditions. Under both conditions, the true target side was selected based on a random number that follows a Bernoulli distribution for each trial. This was to prevent participants from predicting the stepping direction based on the frequency of occurrences in previous trials. Under the dual-equal-probability condition, either of the lateral or medial target (i.e., the right circle or the left circle, respectively) was selected as the true target with 50 % probability. The dual-equal-probability condition was the same occurrence rate as the dual-target condition of Experiment 1 even though the medial target and targets did not necessarily occur in the same number of trials. Under the dual-unequal-probability condition, the lateral target was selected with 80% probability and the medial target was selected with 20% probability. Different colors were used to show the target on the display between the two conditions to clearly differentiate the occurrence probabilities between the two conditions. Under the equal-probability condition, both circles were sky blue. Under the unequal-probability condition, the right circle was light green and the left circle was salmon colored.

Participants performed a total of 240 main trials. Trials were divided into sets of 120 trials per day to avoid fatigue. Each day, participants performed the task for 15 trials under the single-lateral condition, 15 trials under the single-medial condition, 45 trials under the dual-equal-probability condition, and 45 trials under the dual-unequal-probability condition (Fig. 3-1).

To familiarize participants with the task, they performed 16 training trials on both days before the main trials. In this session, participants first completed 8 trials, in which two trials for following target conditions were performed in the sequential order: the single-lateral, single-medial, dual-equal-probability-lateral, and dual-equal-probability-medial conditions. Next, participants completed 6 trials, in which one trial for following target conditions was performed in the random order: the single-lateral, single-medial, dual-equal-probability-lateral, dual-equal-probability-medial, dual-unequal-probability-lateral, and dual-unequal-probability-medial conditions. Additionally, to familiarize participant with the occurrence probability of the dual-target condition, they observed the visual stimuli, which were presented under both the dual-equal-probability and dual-unequal-probability condition, without performing stepping movements. They observed 25 trials of the visual stimuli under the dual-equal-probability and dual-unequal-probability condition, respectively.

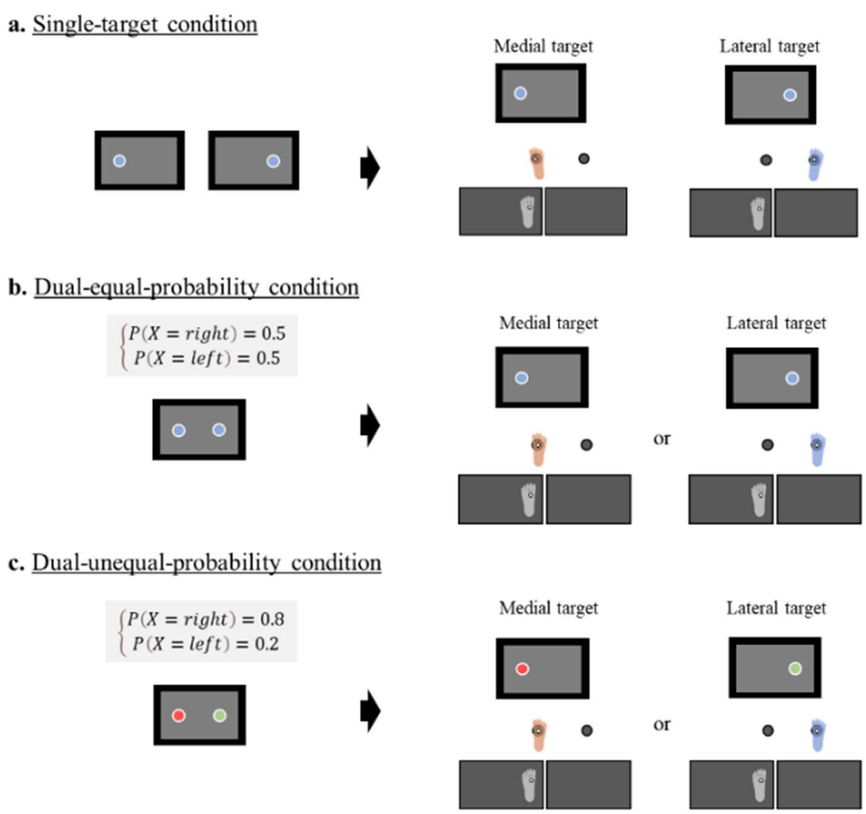

Figure 3-1. Illustration of trial types: (a) single-target condition; (b) dual-equal-probability condition; (c) dual-unequal-probability condition.

3.2.4. Data analyses and statical analyses

The same data analyses as in Experiment 1 were used for mediolateral COP displacements. The main dependent variable was focused only on the lateral displacement of the COP toward the swing foot. For this variable, a two-way (target condition and stepping side) analysis of variance (ANOVA) with repeated measures was used to statistically analyze the dependent variable. The Bayesian estimation procedures were the same as in Experiment 1. Additionally, according to the relationship between the time at the lift-off of the swing foot and the individual's strategy for postural adjustments under the dual-target conditions, a Spearman correlation test was performed for the dual-equal-probability condition and the dual-unequal-probability condition.

3.3. Results

Comparing the magnitudes of the lateral displacements of the COP toward the swing leg between the single- and dual-target conditions

Mean lateral displacements of the COP toward the swing-foot side are shown in Figure 3-2. A two-way ANOVA showed a significant main effect of the stepping side ($F_{(1, 9)} = 31.57$, $p < .001$, $\eta_p^2 = 0.78$). Regarding a factor of stepping sides, lateral displacements of the COP were greater under the medial stepping condition than those under the lateral stepping condition. The interaction was also significant ($F_{(1, 9)} = 42.99$, $p < .001$, $\eta_p^2 = 0.83$).

Two simple main effects were found regarding the interaction between two factors. First, regarding the condition of lateral stepping, lateral displacements of the COP were significantly different among three target conditions ($F_{(1.16, 10.43)} = 12.8$, $p = .004$, $\eta_p^2 = 0.59$). Pairwise t-tests with Holm–Bonferroni corrections revealed that both lateral displacements of the COP under both the dual-equal-probability and dual-unequal-probability conditions were greater than those under the single-target condition (dual-equal-probability: $t_{(9)} = 3.74$, $p = .014$; dual-unequal-probability: $t_{(9)} = 3.58$, $p = .014$). Second, regarding the single-target condition, lateral displacements of the COP under the medial stepping condition were significantly greater than under the lateral stepping condition ($F_{(1, 9)} = 88.64$, $p < .001$, $\eta_p^2 = 0.91$). There were no other significant effects.

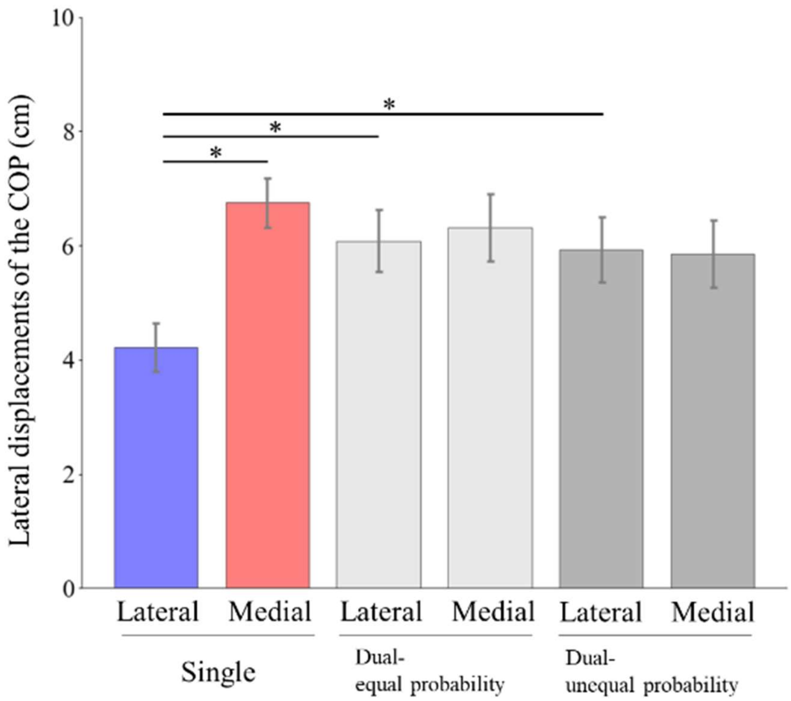

Figure 3-2. Mean lateral displacements of the COP toward the swing-foot side. Error bars represent standard errors of the mean under each condition. An asterisk (*) indicates a significant difference in group means based on post hoc analysis ($p < .05$).

Individual weight between the policies of medial stepping and lateral stepping

Estimated weight values for each participant are shown in Figure 3-3. Under the dual-equal-probability condition, a posterior mean greater than 0.67, which represents the medial-weighting pattern, was observed in six of the 10 participants. Under the dual-unequal-probability condition, a posterior mean greater than 0.67 was observed in the seven of the 10 participants.

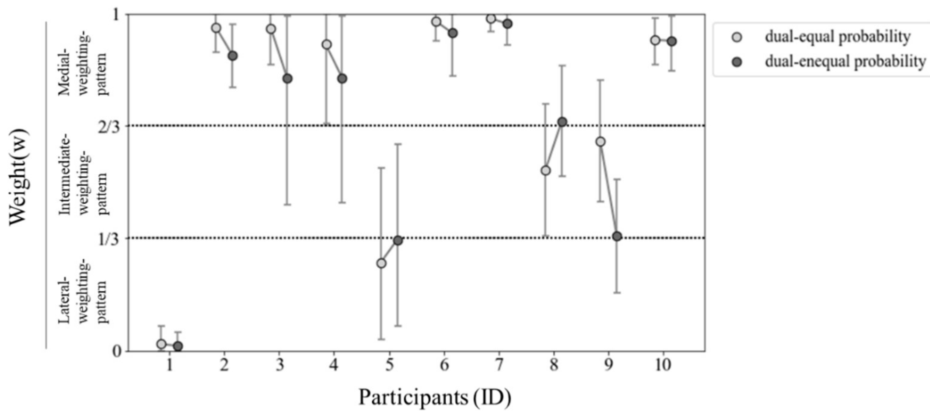

Figure 3-3. Estimated individual weight values between the policies of medial stepping and lateral stepping under the dual-target condition. Dark gray and light gray dots represent the posterior mean of the weight value under the dual-equal-probability and the dual-unequal-probability condition, respectively. Error bars represent a 95% creditable interval for each individual weight value.

Relationships between the timing at lift-off of the swing foot and the individual's strategy of the postural adjustments in the dual-target condition

There were some variations among participants under both the dual-even condition and the dual-uneven condition (Fig. 3-4a). The standard time deviations under the dual-equal-probability and dual-equal-probability conditions were 64.2 ms and 67.4 ms, respectively. Spearman's rank correlation tests showed that the time from the display of the true target to the lift-off of the swing foot was significantly correlated with the posterior mean of the value of weight value under the dual-unequal-probability condition (dual-uneven: r = -0.65, p = .04). Correlations between both variables were marginally significant in the dual-equal-probability condition (r = -0.61, p = .06).

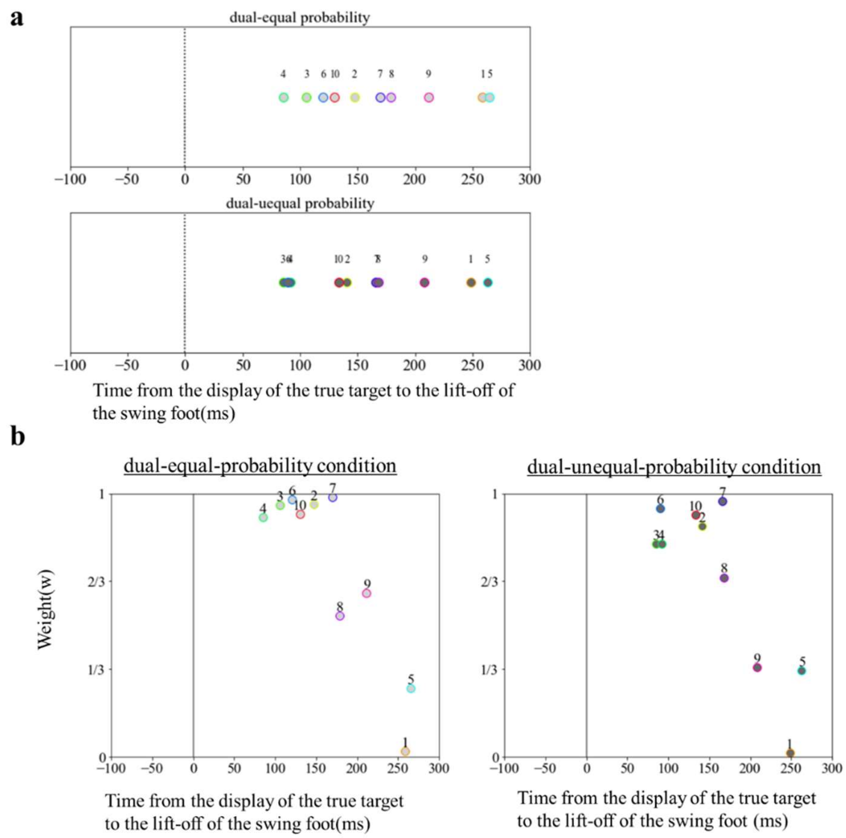

Figure 3-4. (a) Data plots illustrating the time from the display of the stepping circle to the lift-off of the swing foot for each participant. Dark gray and light gray dots represent the average values of these times under the dual-equal-probability and the dual-unequal-probability condition, respectively. Each number by a scatter point represents the participant's ID. (b) Data plots illustrating the relationship between the time from the display of the true target to the lift-off of the swing foot and posterior mean of the estimated weight value under the dual-equal-probability condition (left panel) or dual-unequal-probability condition (right panel).

3.4. Discussion

As hypothesized, lateral COP displacements under the dual-unequal-probability condition were similar to those when the medial target was selected under the single-target condition. Bayesian estimations of individual strategies also showed, even when the lateral target was selected more frequently, that the medial weighting pattern was chosen consistently by more than half of the participants. These results suggest that the cost of maintaining postural stability is likely to be emphasized more than the occurrence probability of competing options.

In Experiment 2-1, some participants delayed their foot lift until after the display of the true target. These participants were categorized as showing intermediate-weighting or lateral-weighting patterns. Considering that the true target was displayed before the lift-off of the swing foot, it is possible that such participants shifted their weight slowly to ensure that they would have enough time to judge the correct stepping direction before the lift-off of the swing foot. Therefore, I considered that the individual COP patterns of these participants did not necessarily represent postural strategies based on the occurrence probability of competing targets. To avoid individual differences in the timing of the lift-off of the swing foot, I conducted Experiment 2-2, in which the same hypothesis was tested with an alteration of the task setting so that the true target was displayed after the swing foot had left the ground.

CHAPTER 4: Experiment 2-2

4.1. Purpose

In Experiment 2-2, the true target was displayed after the swing foot had left the ground. Therefore All participants had to lift the swing foot without knowing which of the potential targets would be the true one. This enabled me to test whether the desirability of the probability of competing options or the cost of maintaining postural stability was a dominant in preparing their postures prior to stepping movements.

Further, I verified whether, in addition to the COP displacements, subsequent kinematic states of the pelvis were also planned based on the cost of maintaining postural stability. I used the velocity of the pelvis at the lift-off of the swing foot. The velocity of the pelvis has been used to represent the mediolateral body movement (Rankin et al., 2014; Wang and Srinivasan, 2014). Before the lift-off of the swing foot, COP displacements toward the swing-foot side occur. Theoretically, greater COP displacements generate larger propulsive forces toward the stance-foot side and induce a greater acceleration of the pelvis toward the stance foot. These preparations lead to moving the pelvis toward the stance-foot side (i.e., the medial side). It was expected that the mediolateral velocity of the pelvis with two potential targets would be scaled similar to those when the single target exists on the medial side, irrespective of the occurrence probability.

4.2. Material and Methods

4.2.1. Participants

Seven participants were recruited (five males and two females; age: 24.3 ± 5.4 years; height: 167.4 ± 9.8 cm; weight: 60.3 ± 11.9 kg). One male participated on only one day due to his personal circumstances. The procedures and criteria of participation are the same as in Experiment 1. This experiment was approved by the Ethics Committee of Tokyo Metropolitan University (approval number: H4-88).

4.2.2. Apparatus

The same apparatus as in Experiment 2-1 was used, with the exception that the threshold of the display of the target was changed from the time of the first peak of the vertical force on the swing-foot side to after the vertical force fell to 10 % of the total body weight. This threshold value was chosen as the time that the true target was displayed after participants lifted their swing foot off the ground, considering a time delay for the display of the visual stimuli on the screen.

4.2.3. Task and procedure, data analyses, and statistical analyses

The same task and statistical analyses. as in Experiment 2-1 were used. Procedures for analyzing COP data were the same in Experiment 2-1 except for changing the definition about the peak point of mediolateral COP displacement from the first peak to the maximum peak point of the COM movement toward the swing-foot side. The reason for this change is that, in Experiment 2-2, it was not necessary to consider the corrections of COP movements before the lift-off according to the display of the true target. The mediolateral velocity of the pelvis was determined as the mean mediolateral velocity of the pelvis toward the stance-foot side at the time of lift-off of the swing foot.

4.3. Results

Comparing lateral COP displacements toward the swing-foot side between the single- and dual-target conditions

A two-way ANOVA showed significant main effects of types of targets ($F_{(1.09, 6.55)}$ = 8.16, p = .025, η_p^2 = 0.58) and the stepping side ($F_{(1, 6)}$ = 56.01, p < .001, η_p^2 = 0.90). The interaction was also significant ($F_{(1, 12)}$ = 31.07, p < .001, η_p^2 = 0.84).

Regarding the main effect of the target condition, lateral displacements of the COP under the dual-equal-probability condition were significantly greater than those under the single-target condition (t(6) = 4.09, p = .019). Regarding the interaction between two factors, three simple main effects were found First, when stepping onto the lateral target, lateral displacements of the COP were significantly different among three target conditions ($F_{(1.16, 6.94)}$ = 39.78, p < .001, η_p^2 = 0.87). Post-hoc t-tests with Holm–Bonferroni corrections revealed that lateral displacements of the COP under both the dual-equal-probability and the dual-equal-probability condition were greater than those under the single-lateral condition ($t_{(6)}$ = 8.14, p = .001; $t_{(6)}$ = 5.23, p = .004). Additionally, lateral displacements of the COP under the dual-equal-probability condition were greater than those under the dual-unequal-probability condition (t(6) = 3.19, p = .02). Second, under the single-target condition, lateral displacements of the COP under the medial stepping condition were significantly greater than those under the lateral stepping condition ($F_{(1, 6)}$ = 52.91, p < .001, η_p^2 = 0.90). Third, under the dual-unequal-probability condition, lateral displacements of the COP under the medial stepping condition were significantly greater than those under the lateral stepping condition ($F_{(1.16, 6.94)}$ = 7.88, p = .031, η_p^2 = 0.57). There were no other significant differences.

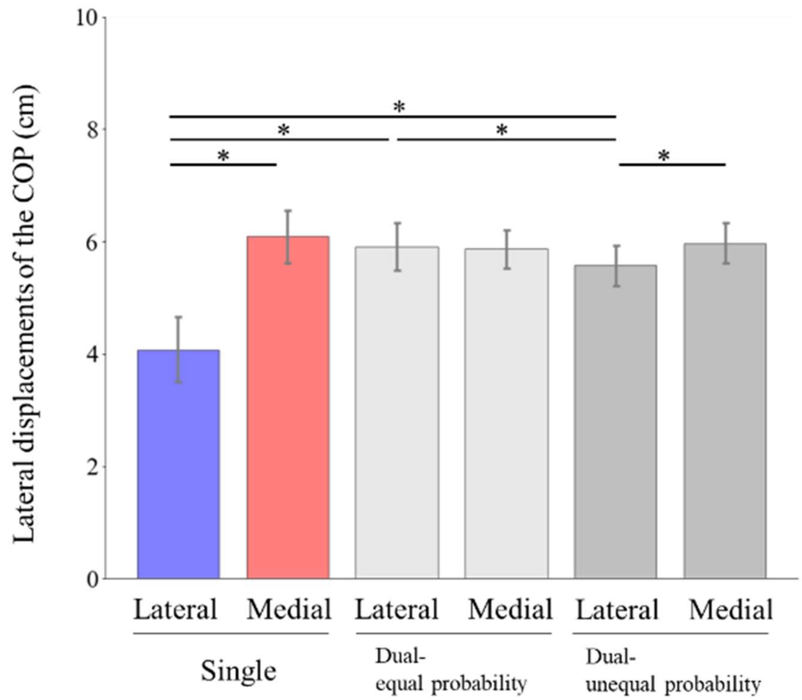

Figure 4-1. Mean lateral displacements of the COP toward the swing-foot side. See the caption of Figure 2-4 in section 2.3 for details.

Individual weight between the policies of medial stepping and lateral stepping

Estimated weight values for each participant are shown in Figure 4-2. Under the dual-equal-probability condition, a posterior mean greater than 0.67, which represents the medial-weighting pattern, was observed in six of the seven participants. Under the dual-unequal-probability condition, a posterior mean greater than 0.67 was observed in three of the seven participants.

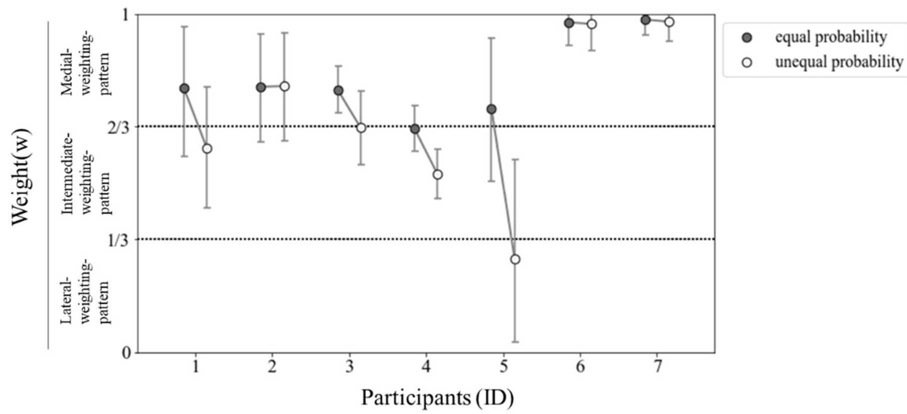

Figure 4-2. Estimated individual weight values between the policies of medial stepping and lateral stepping under the dual-equal-probability and dual-unequal-probability conditions. See the caption of Figure 2-5 in section 2.3 for details.

Relationships between the time of lift-off of the swing foot and the individual's strategy for the postural adjustments under the dual-target condition

For all participants, the time of the lift-off of the swing foot was after the display of the true target. Standard deviations in timings under the dual-equal-probability and dual-unequal-probability conditions were 8.8 ms and 9.2 ms, respectively. Spearman's rank correlation tests showed that no significant correlations were found between the time from the display of the true target to the lift-off of the swing foot and the posterior mean of the weight value under either the dual-equal-probability condition or the dual-unequal-probability condition (dual-equal-probability: $p = .22$; dual-unequal-probability: $p = .59$).

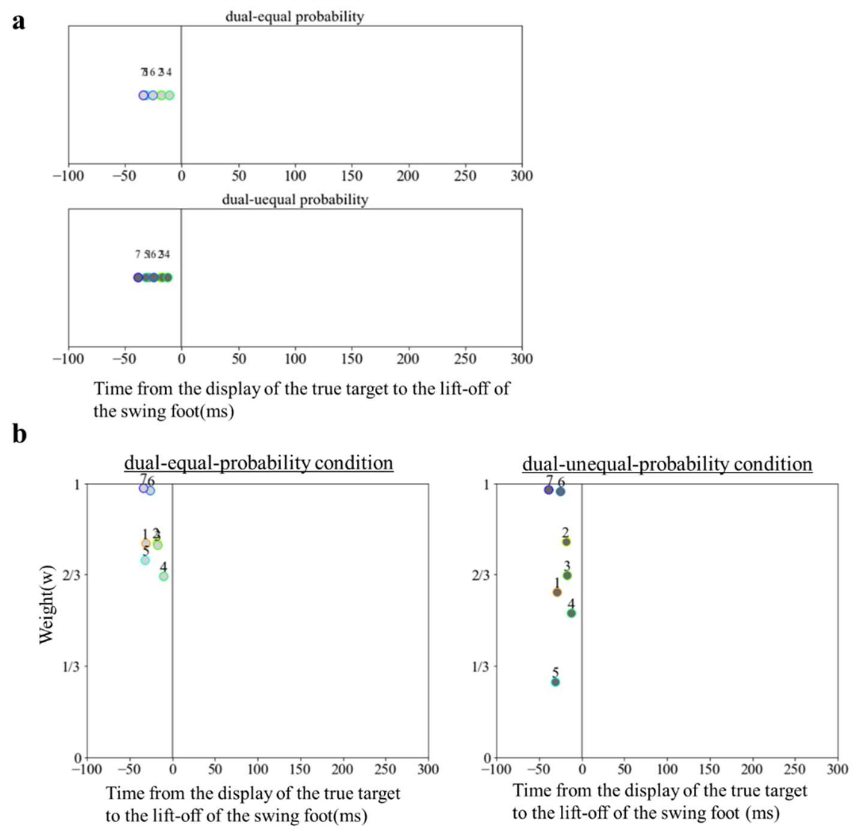

Figure 4-3. (a) Data plots illustrating the time from the display of the stepping circle to the lift-off of the swing foot for each participant. (b) Data plots illustrating the relationship between the time from the display of the true target to the lift-off of the swing foot and the posterior mean of the weight value under the dual-equal-probability condition (left panel) and dual-unequal-probability condition (right panel).

Mediolateral velocity of the pelvis toward the stance-foot side

A two-way ANOVA showed significant main effects of the target condition ($F_{(1.13, 6.77)}$ = 13.33, p = .008, η_p^2 = 0.69) and the stepping side ($F_{(1,6)}$ = 75.59, p < .001, η_p^2 = 0.93). The interaction was also significant ($F_{(1.12, 6.72)}$ = 35.61, p < .001, η_p^2 = 0.86).

Regarding the main effect of the target condition, the mediolateral velocity of the pelvis under both the dual-equal-probability and the dual-unequal-probability conditions was significantly higher than that under the single-lateral condition (dual-equal probability: p = .012, dual-unequal probability: p = .046). Regarding the interaction between two factors, three simple main effects were found. First, when stepping onto the lateral target, the mediolateral velocity of the pelvis was significantly different among three target conditions ($F_{(1.06, 6.38)}$ = 32.82, p < .001, η_p^2 = 0.85). Post-hoc t-tests with Holm–Bonferroni corrections revealed that the mediolateral velocity of the pelvis under both the dual-equal-probability and the dual-unequal-probability conditions was significantly faster than those in the single-lateral condition (dual-equal probability: p = .001, dual-unequal probability: p = .006). Additionally, the mediolateral velocity of the pelvis under the dual-equal-probability condition was significantly higher than that under the dual-unequal-probability condition (p = .014). Second, according to the single-target condition, the mediolateral velocity of the pelvis under the medial stepping condition was significantly higher than that under the lateral stepping condition ($F_{(1, 6)}$ = 57.02, p < .001, η_p^2 = 0.90). Third, according to the dual-unequal-probability condition, the mediolateral velocity of the pelvis under the medial stepping condition was significantly faster than those in the lateral stepping condition ($F_{(1, 6)}$ = 7.2, p = .036, η_p^2 = 0.55). There were no other significant differences.

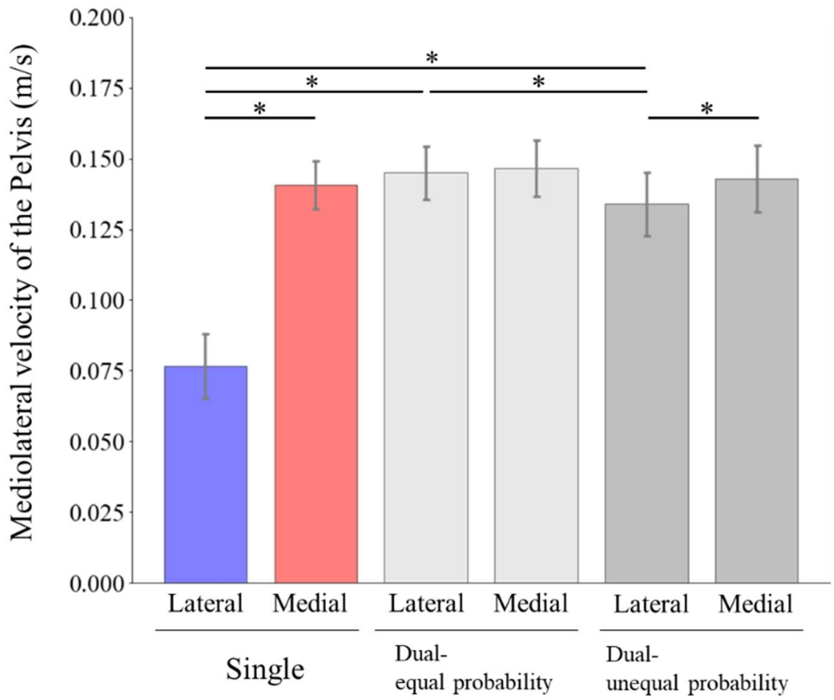

Figure 4-4. Mean mediolateral velocity of the pelvis at the lift-off of the swing foot. An asterisk (*) indicates a significant difference in group means based on post hoc analysis ($p < .05$).

4.4. Discussion

In this experiment, the individual differences in timing of the display of the true target after the lift-off of the swing foot from the ground were relatively small compared to those of Experiment 2-1. Additionally, I verified that the timing was not correlated with individual postural patterns. This indicated that, in Experiment 2-2, individual postural patterns were selected irrespective of the timing of the target display.

Regarding COP displacements, the results mostly replicated those of Experiment 2-1; lateral COP displacements under the dual-unequal-probability condition, in which the lateral target was selected more frequently than the medial target, were similar to those when the medial target was selected under the single-target condition. Notably, Bayesian estimations of individual patterns showed only three out of seven participants selected the medial-weighting patterns when the lateral target was more likely. Therefore, not all participants prepared their posture for easy stepping toward the medial side.

The results of the mediolateral velocity of the pelvis, which was newly added as another main outcome, also supported the hypothesis. The pelvis velocity under the dual-unequal-probability condition was similar to that when the single target existed on the medial side. This indicated that, when landing locations were unknown until the lift-off of the swing foot, the kinematic state of the pelvis was also controlled for easy stepping toward the medial side. Similar to this, a previous study reported that the velocity of the COM toward the stance-foot side at the lift-off of the swing foot was higher when the individual intended to move in the medial direction (Corbeil and Anaka, 2011). Considering both my findings and those of the previous study, sufficient pelvis velocity toward the stance-foot side at the lift-off of the swing foot would lead to a subsequent body trajectory in the medial direction after initiation of the stepping movement. This would contribute to stabilizing posture without additional efforts to control upright balance even when landing on the medial target.

CHAPTER 5: Experiment 3

5.1. Purpose

The purpose of Experiment 3 was to address whether the cost of maintaining postural stability continued to be dominant even when the gain of the lateral target was higher. For this purpose, I introduced the feedback about the gain with successful stepping. Participants obtained scores assigned to each of two potential targets. Specifically, participants performed dual-target trials both under the equal-gain condition (medial : lateral = 5 : 5) and under the unequal-gain condition (medial : lateral = 2 : 8). If the cost of maintaining postural stability was a dominant consideration, then both the lateral displacements of the COP and the mediolateral velocity of the pelvis with two potential targets would be similar to those when a single target existed on the individual's medial side, regardless of the gain from competing options.

5.2. Material and Methods

5.2.1. Participants

Nine participants were recruited (four males and five females; age: 24.9 ± 8.1 years; height: 167.7 ± 12.5 cm; weight: 61.9 ± 15.1 kg). The procedures and criteria of participation were the same as in Experiment 1, 2-1, and 2-2. The data for Day 1, obtained from two participant (ID1 and ID2), was excluded from the following analysis due to system failure. This experiment was approved by the Ethics Committee of Tokyo Metropolitan University (approval number: H4-88).

5.2.2. Apparatus, task, data analyses, and statistical analyses

In Experiment 3, when stepping onto the correct target, the score assigned to that target was given to the participants. To verify whether participants accurately stepped onto the correct target, I newly measured the location of each foot. This was implemented by the real-time monitoring of the tracker attached to each participant at the second-metatarsal bone head of the stepping-foot (Fig. 5-1).

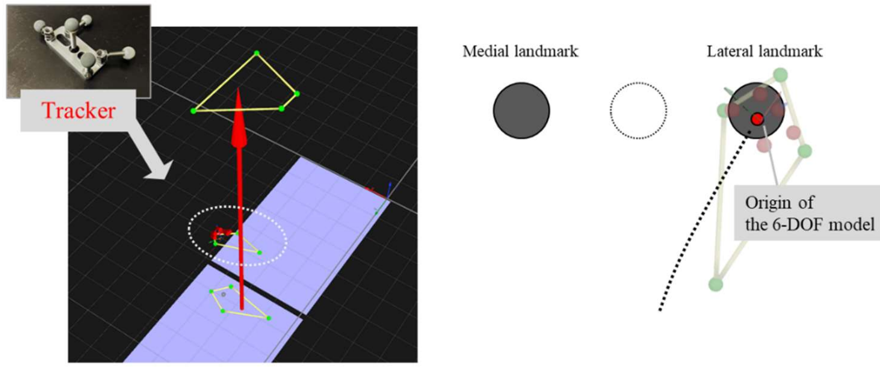

Figure 5-1. Methods for judging stepping onto the correct target. When the tracker attached to the swing foot enters the circle of the true targets, the score assigned to that target was given to the participants.

Participants performed a total of 260 main trials for two consecutive days. They performed 130 trials (five blocks of 26 trials) per day to avoid fatigue. Each block, participants performed the task for six trials under the single-target condition and 20 dual-target trials. Under the single-target condition, each of the medial and lateral targets appeared for three trials. Under the dual-target condition, both the equal-gain condition and the unequal-gain condition was performed. Under the dual-equal-gain condition, each of the medial and lateral targets was selected as the true target for five trials. Under the dual-unequal-gain condition, each of the medial and lateral targets was selected as the true target for five trials. Under the single-target condition, only the medial or lateral targets appeared for the respective trials; the score was 5 points. Under the dual-equal-gain condition, 5 points were assigned to the lateral target and 5 points were assigned to the medial target (i.e., the right circle and left circle, respectively). Under the dual-unequal-gain condition, 8 points were assigned to the lateral target, and 2 points were assigned to the medial target. To clearly show the condition under which participants were performing, the target on the display was shown in different colors depending on the conditions. Under the dual-equal-gain condition, both medial and lateral targets were sky blue. Under the dual-unequal-gain condition, the lateral target was light green and the medial target was salmon colored. When participants accurately landed on the correct target, the character for “Good!” was displayed on the screen and participants received the designated points. Participants were instructed to perform the task while striving to achieve the maximum number of points possible in each block.

To familiarize participants with the task, they performed 16 training trials on both days before the main trials. In these trials, participants first completed 8 trials, in which two trials for following target conditions were performed in the sequential order: the single-lateral, single-medial, dual-equal-gain-lateral, and dual-equal-gain-medial conditions. Next, participants completed 6 trials, in which one trial for following target conditions was performed in the random order: the single-lateral, single-medial, dual-equal-gain-lateral, dual-equal-gain -medial, dual-unequal-gain-lateral, and dual-unequal-gain-medial conditions. Additionally, to familiarize participant with the score obtained under each target condition, they observed the visual stimuli without performing stepping movements. They observed 26 trials of visual stimuli, in which were the same as used in the main trials.

The same data analyses and statistical analyses as in Experiment 2-2 were used.

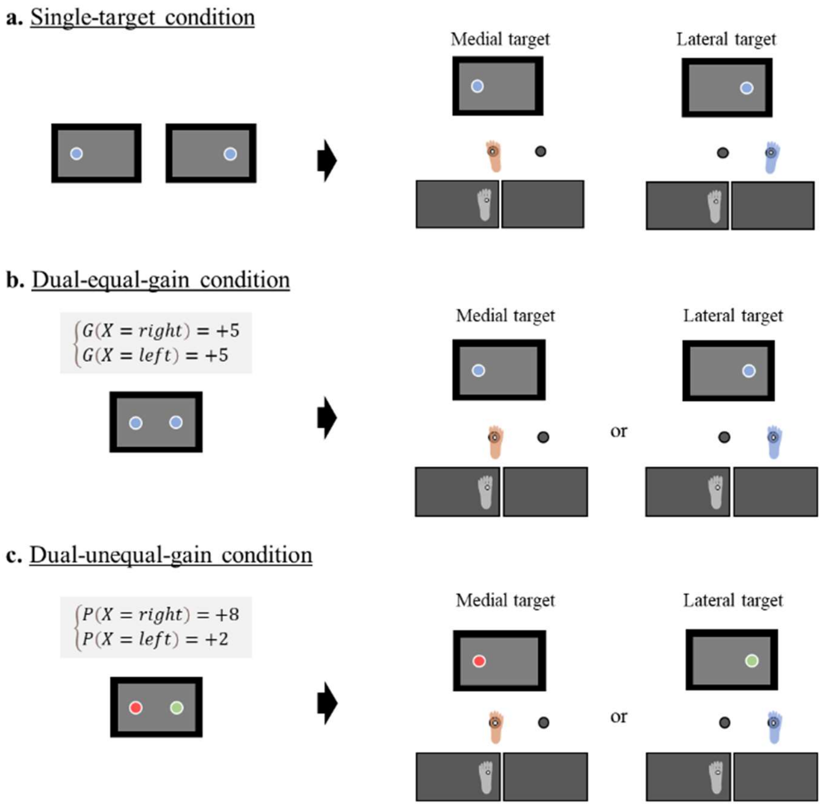

Figure 5-2. Illustration of trial types: (a) single-target condition; (b) dual-equal-gain condition; (c) dual-unequal-gain condition.

5.3. Result

Comparing the magnitudes of the lateral displacements of the COP toward the swing-foot side between the single- and dual-target conditions

A two-way ANOVA showed a significant main effect of the stepping side ($F_{(1, 8)}$ = 68.11, $p < .001$, $\eta_p^2 = 0.89$). The interaction was also significant ($F_{(1.05, 8.43)}$ = 28.09, $p < .001$, $\eta_p^2 = 0.78$).

Three simple main effects were found regarding the interaction between two factors. First, when stepping onto the lateral target, lateral displacements of the COP were significantly different among three target conditions ($F_{(1.1, 8.78)}$ = 8.07, p = .018, $\eta_p^2 = 0.50$). Post-hoc t-tests with Holm–Bonferroni corrections revealed that, the lateral displacements of the COP under the dual-unequal-gain condition were significantly greater than those under the single-lateral condition ($t_{(8)}$ = 3.06, p = .047). Lateral displacements of the COP under the dual-equal-gain condition were also greater than those under the single-lateral condition, but this differences failed to reach statistical significance ($t_{(8)}$ = 2.70, p = .054). Second, when stepping onto the medial target, lateral displacements of the COP were significantly different among three target conditions ($F_{(2, 16)}$ = 7.86, p = .004, $\eta_p^2 = 0.50$). Post-hoc t-tests with Holm–Bonferroni corrections revealed that lateral displacements of the COP under the dual-equal-gain condition were less than those under the single-medial condition ($t_{(8)}$ = 3.29, p = .033). Lateral displacements of the COP under the dual-unequal-gain condition were also less than those under the single-medial condition, but the difference failed to reach statistical significance ($t_{(8)}$ = 2.57, p = .067).Third, under the single-target condition, lateral displacements of the COP under the medial stepping condition were significantly greater than those under the lateral stepping condition ($F_{(1, 8)}$ = 42.57, $p < .001$, $\eta_p^2 = 0.84$). There were no other significant differences.

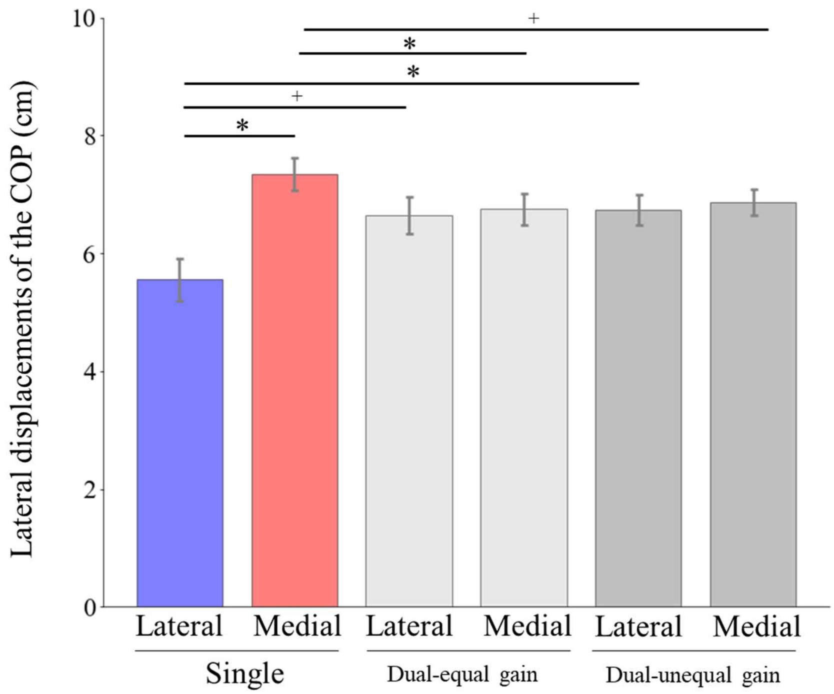

Figure 5-3. Mean lateral displacements of the COP toward the swing-foot side. An asterisk (*) indicates a significant difference in group means based on post hoc analysis ($p < .05$). A plus sign (+) indicates a marginally significant difference in group means based on post hoc analysis ($p < .10$).

Individual weight between the policies of medial stepping and lateral stepping

Estimated weight values for each participant are shown in Figure5-4. Under the dual-equal-gain condition, a posterior mean greater than 0.67, which represents the medial-weighting pattern, was observed in four of the nine participants. Under the dual-unequal-gain condition, the posterior mean greater than 0.67 was observed in four of the nine participants.

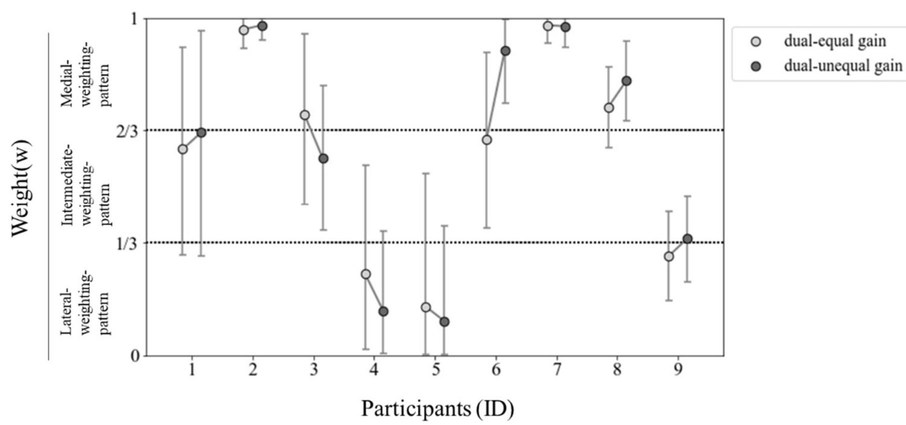

Figure 5-4. Estimated individual weight values between the policies of medial stepping and lateral stepping under the dual-equal-gain condition and the dual-unequal-gain condition. Dark gray and light gray dots represent the posterior mean of the weight value under the dual-equal-gain and dual-unequal-gain condition, respectively. Error bars represent a 95% creditable interval for each estimated value.

Mediolateral velocity of the pelvis toward the stance foot side

A two-way ANOVA showed significant main effects of the target condition ($F_{(1.01,\ 8.07)}$ = 21.75, p = .002, η_p^2 = 0.73) and the stepping side ($F_{(1,8)}$ = 62.47, p < .001, η_p^2 = 0.89). The interaction was also significant ($F_{(1.06,\ 8.45)}$ = 44.33, p < .001, η_p^2 = 0.85).

Regarding the main effect of the target condition, the mediolateral velocity of the pelvis under both the dual-equal-probability and the dual-unequal-probability conditions was significantly higher than that under the single-target condition (dual-equal-probability: p = .004; dual-unequal-probability: p = .004). Regarding the interaction between two factors, two simple main effects were found. First, when stepping onto the lateral target, the mediolateral velocity of the pelvis was significantly different among three target conditions ($F_{(1.02,\ 8.14)}$ = 37.50, p < .001, η_p^2 = 0.82). Post-hoc t-tests with Holm–Bonferroni corrections revealed that the mediolateral velocity of the pelvis under both the dual-equal-probability and the dual-unequal-probability conditions was significantly higher than that under the single-lateral condition (dual-equal-probability: p < .001; dual-unequal-probability: p = .001). Second, regarding the single-target condition, the mediolateral velocity of the pelvis under the medial stepping condition was significantly higher than that under the lateral stepping condition ($F_{(1,\ 8)}$ = 57.74, p < .001, η_p^2 = 0.88). There were no other significant differences.

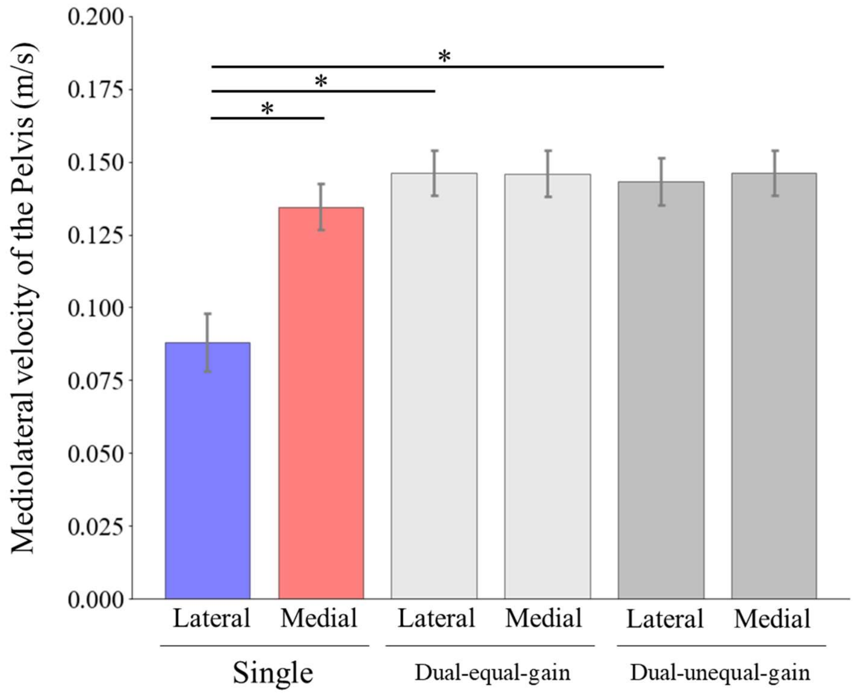

Figure 5-5. Mean mediolateral velocity of the pelvis at the lift-off of the swing foot from the ground. An asterisk (*) indicates a significant difference in group means based on post hoc analysis ($p < .05$).

5.4. Discussion

The results of the lateral COP displacements did not clearly support my hypothesis. The lateral COP displacements under both the dual-equal-gain and dual-unequal-gain conditions were shifted more greatly than those when the single target existed on the lateral side but less than those when the single target existed on the medial side. Bayesian estimation of individual COP patterns showed that four of nine participants selected the medial-weighing patterns, suggesting that the actions of some participants aligned with the hypothesis.

In contrast, the results for mediolateral velocity of the pelvis were consistent with the hypothesis; the velocity at the lift-off of the swing foot was scaled similar to that when the single target existed on the medial side under both the dual-equal-gain and dual-unequal-gain conditions. This indicates that at least the body state at the lift-off of the swing foot was regulated effectively to step onto the medial target regardless of the gains from competing options.

As to why the results for mediolateral COP displacements did not follow those of the other experiments (i.e., Experiments 1, 2-1, and 2-2), the COP regulation may have been affected by the increase in effort to achieve gains. In this stepping task, the feedback about the gain with successful stepping was newly implemented in Experiment 3. This setting would increase the effort to achieve gains by precisely adjusting the foot on each target. It is possible that for some participants (e.g., ID4 and ID5), when stepping on the medial target, it took less effort to adjust their foot accurately than to step on the lateral target. Therefore, under both the dual-equal-gain and dual-unequal-gain conditions, such participants may have shifted their COP for easy stepping onto the lateral target.

CHAPTER 6: General Discussion

Throughout the four experiments, I addressed whether the cost of maintaining postural stability were considered more dominantly than the values of competing options when planning an action that involves maintaining balance under multiple competing options. I found that, for the majority of experiments (Experiments 1, 2-1, and 2-2), mediolateral COP displacements with two potential targets were regulated for easy stepping onto the medial target. Such COP patterns were observed even when preparing to step toward the lateral side was more reasonable in terms of the occurrence probability (Experiment 2-1 and 2-2). The velocity of the pelvis at the lift-off of the swing, which was introduced in Experiments 2-2, was also regulated for easy stepping onto the medial target regardless of the occurrence probability or gains from competing options (Experiment 2-2 and Experiment 3). Considering these findings, I conclude that the cost of maintaining postural stability were emphasized more than the value of competing options.

It has been suggested that the brain considers two factors when planning an anticipatory action—the value of competing options and the cost of each potential action (Christopoulos and Schrater, 2015; Enachescu et al., 2021). This model was mainly constructed based on studies using the motion of the arm while the rest of the body. Therefore, a dominant factor for action planning that involves maintaining upright balance was unclear. What I found in the present study was that the cost of maintaining postural stability was considered predominantly when individuals prepared their posture for stepping movements. I used a “go-before-you-know” task to have participants step onto either the medial or lateral target and showed that COP displacement (Experiments 1, 2-1, and 2-2) and pelvis velocity (Experiments 2-2 and 3) were regulated for easy stepping toward the medial side. This was the case even when the medial target was selected as the true target less frequently or brought with low gains with success. Considering that the mediolateral postural stability at landing on the medial target decreased than that at landing on the lateral target, it is assumed that the brain prioritized postural preparations for an action option that have a higher risk to avoid postural destabilization. The results suggest that the brain regards the cost of maintaining postural stability as the dominant factor and controls states of posture to ensure postural stabilization in any case until the true stepping side is revealed.

Setting a pre-step posture optimized for stepping toward the medial side would also provide benefits for accurate reorientation of the foot toward the true target. It is thought that one of functional roles of postural adjustment is to predictively minimize perturbations with movements of the end effector toward intended directions (Leonard et al., 2009). Once individuals ensure upcoming postural stabilization, then they would be able to correct their foot trajectories toward the true target, as in the stepping task with balance supports (Nonnekes et al., 2010; Reynolds and Day, 2005). Additionally, sufficient acceleration of the COM toward the stance-foot side following greater COP displacements lengthens the duration of lifting the swing foot from the ground and affords more time to achieve accurate stepping (Yamada and Shinya, 2021). In light of this evidence, I suggest that the brain plans an anticipatory action effectively for performing the stepping task successfully while maintaining postural stability.

I regard a medial weighting pattern of postural control strategies as the optimal plan for maintaining postural stability when stepping onto a target accurately. However, a different interpretation would also be possible. For example, the results could also be explained in terms of energy efficiency while reorienting the swing foot toward the medial side (as discussed in Section 1-3 of Introduction and Literature Review). A previous study has shown that the brain implements an action that minimizes the effort to correct actions after the true target has been revealed (Nashed et al., 2017; Wong and Haith, 2017). To correct body movements toward the medial side after the lift-off of the swing foot, greater torque is necessary because the body movements fall toward the swing-foot side due to the effects of gravity. If the body is shifted toward the swing-foot side (i.e., the medial side) until the lift-off of the swing foot, stepping onto the medial target would ultimately be accomplished with relatively little torque generation. Considering this fact, I cannot rule out the possibility that significant displacements of the COP and acceleration of the pelvis under the dual-target condition showed that the brain placed emphasis on energy efficiency, rather than postural instabilities, when correcting the swing foot during a swing phase. Future studies need to address which explanation—the cost of maintaining balance or energy efficiency—would be more suitable for the phenomenon of postural adjustment for stepping on one of two potential targets.

Conclusion

In the above four experiments, I revealed a rule for anticipatory action planning for stepping onto two potential targets. When individuals prepare their posture for stepping movements without knowing which of the potential options should be selected, the cost of maintaining postural stability affected action planning more dominantly than the values of options. Even when either of two potential options was more frequent or promised high gains, a certain number of participants more effectively controlled their posture for stepping toward the option that would potentially cause postural destabilization. I believe this evidence provides a framework for understanding the rule of an action that involves maintaining upright balance.

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Ryo Watanabe
January 5, 2023

References

Aimola, E., Santello, M., la Grua, G., & Casabona, A. (2011). Anticipatory postural adjustments in reach-to-grasp: Effect of object mass predictability. *Neuroscience Letters*, *502*(2), 84–88. https://doi.org/10.1016/j.neulet.2011.07.027

Alhussein, L., & Smith, M. A. (2021). Motor planning under uncertainty. *ELife*, *10*. https://doi.org/10.7554/eLife.67019

Bancroft, M. J., & Day, B. L. (2016). The throw-and-catch model of human gait: Evidence from coupling of pre-step postural activity and step location. *Frontiers in Human Neuroscience*, *10*(DEC2016). https://doi.org/10.3389/fnhum.2016.00635

Brooks, J., & Thaler, A. (2017). The sensorimotor system minimizes prediction error for object lifting when the object's weight is uncertain. *Journal of Neurophysiology*, *118*(2). https://doi.org/10.1152/jn.00232.2017

Bruijn, S. M., & van Dieën, J. H. (2018). Control of human gait stability through foot placement. In *Journal of the Royal Society Interface* (Vol. 15, Issue 143). Royal Society Publishing. https://doi.org/10.1098/rsif.2017.0816

Cashaback, J. G. A., McGregor, H. R., Pun, H. C. H., Buckingham, G., & Gribble, P. L. (2017). Does the sensorimotor system minimize prediction error or select the most likely prediction during object lifting? *Journal of Neurophysiology*, *117*(1). https://doi.org/10.1152/jn.00609.2016

Chapman, C. S., Gallivan, J. P., Wong, J. D., Wispinski, N. J., & Enns, J. T. (2015). The snooze of lose: Rapid reaching reveals that losses are processed more slowly than gains. *Journal of Experimental Psychology: General*, *144*(4), 844–863. https://doi.org/10.1037/xge0000085

Chapman, C. S., Gallivan, J. P., Wood, D. K., Milne, J. L., Culham, J. C., & Goodale, M. A. (2010). Reaching for the unknown: Multiple target encoding and real-time decision-making in a rapid reach task. *Cognition*, *116*(2), 168–176. https://doi.org/10.1016/j.cognition.2010.04.008

Christopoulos, V., & Schrater, P. R. (2015). Dynamic Integration of Value Information into a Common Probability Currency as a Theory for Flexible Decision Making. *PLoS Computational Biology*, *11*(9). https://doi.org/10.1371/journal.pcbi.1004402

Corbeil, P., & Anaka, E. (2011). Combined effects of speed and directional change on postural adjustments during gait initiation. *Journal of Electromyography* *and Kinesiology*, *21*(5), 734–741. https://doi.org/10.1016/j.jelekin.2011.05.005

Cos, I., Bélanger, N., & Cisek, P. (2011). The influence of predicted arm biomechanics on decision making. *Journal of Neurophysiology*, *105*(6). https://doi.org/10.1152/jn.00975.2010

Eckerle, J. J., Berg, W. P., & Ward, R. M. (2012). The effect of load uncertainty on anticipatory muscle activity in catching. *Experimental Brain Research*, *220*(3–4), 311–318. https://doi.org/10.1007/s00221-012-3139-z

Enachescu, V., Schrater, P., Schaal, S., & Christopoulos, V. (2021). Action planning and control under uncertainty emerge through a desirability-driven competition between parallel encoding motor plans. *PLoS Computational Biology*, *17*(10). https://doi.org/10.1371/journal.pcbi.1009429

Gallivan, J. P., Chapman, C. S., Wolpert, D. M., & Flanagan, J. R. (2018). Decision-making in sensorimotor control. In *Nature Reviews Neuroscience* (Vol. 19, Issue 9, pp. 519–534). Nature Publishing Group. https://doi.org/10.1038/s41583-018-0045-9

Hof, A. L., Gazendam, M. G. J., & Sinke, W. E. (2005). The condition for dynamic stability. *Journal of Biomechanics*, *38*(1), 1–8. https://doi.org/10.1016/j.jbiomech.2004.03.025

Honeine, J. L., Schieppati, M., Crisafulli, O., & Do, M. C. (2016). The neuro-mechanical processes that underlie goal-directed medio-lateral APA during gait initiation. *Frontiers in Human Neuroscience*, *10*(AUG2016). https://doi.org/10.3389/fnhum.2016.00445

Hudson, T. E., Maloney, L. T., & Landy, M. S. (2007). Movement planning with probabilistic target information. *Journal of Neurophysiology*, *98*(5), 3034–3046. https://doi.org/10.1152/jn.00858.2007

le Mouel, C., & Brette, R. (2017). Mobility as the purpose of postural control. *Frontiers in Computational Neuroscience*, *11*. https://doi.org/10.3389/fncom.2017.00067

Leonard, J. A., Brown, R. H., & Stapley, P. J. (2009). Reaching to multiple targets when standing: The spatial organization of feedforward postural adjustments. *Journal of Neurophysiology*, *101*(4), 2120–2133. https://doi.org/10.1152/jn.91135.2008

MacKinnon, C. D., Bissig, D., Chiusano, J., Miller, E., Rudnick, L., Jager, C., Zhang, Y., Mille, M. L., & Rogers, M. W. (2007). Preparation of anticipatory postural adjustments prior to stepping. *Journal of Neurophysiology*, *97*(6), 4368–4379. https://doi.org/10.1152/jn.01136.2006

Moraes, R. (2014). A model for selecting alternate foot placement during human locomotion. *Psychology and Neuroscience*, *7*(3), 319–329. https://doi.org/10.3922/j.psns.2014.038

Moraes, R., Allard, F., & Patla, A. E. (2007). Validating determinants for an alternate foot placement selection algorithm during human locomotion in cluttered terrain. *Journal of Neurophysiology*, *98*(4), 1928–1940. https://doi.org/10.1152/jn.00044.2006

Nashed, J. Y., Diamond, J. S., Gallivan, J. P., Wolpert, D. M., & Flanagan, J. R. (2017). Grip force when reaching with target uncertainty provides evidence for motor optimization over averaging. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-10996-6

Nonnekes, J. H., Talelli, P., de Niet, M., Reynolds, R. F., Weerdesteyn, V., & Day, B. L. (2010). Deficits underlying impaired visually triggered step adjustments in mildly affected stroke patients. *Neurorehabilitation and Neural Repair*, *24*(4), 393–400. https://doi.org/10.1177/1545968309348317

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Pierrieau, E., Lepage, J. F., & Bernier, P. M. (2021). Action costs rapidly and automatically interfere with reward-based decision-making in a reaching task. *ENeuro*, *8*(4). https://doi.org/10.1523/ENEURO.0247-21.2021

Rankin, B. L., Buffo, S. K., & Dean, J. C. (2014). A neuromechanical strategy for mediolateral foot placement in walking humans. *Journal of Neurophysiology*, *112*(2). https://doi.org/10.1152/jn.00138.2014

Reynolds, R. F., & Day, B. L. (2005). Rapid visuo-motor processes drive the leg regardless of balance constraints. *Current Biology*, *15*(2), R48–R49. https://doi.org/10.1016/J.CUB.2004.12.051

Stewart, B. M., Gallivan, J. P., Baugh, L. A., & Flanagan, J. R. (2014). Motor, not visual, encoding of potential reach targets. In *Current Biology* (Vol. 24, Issue 19, pp. R953–R954). Cell Press. https://doi.org/10.1016/j.cub.2014.08.046

Sun, R., Cui, C., & Shea, J. B. (2017). Aging effect on step adjustments and stability control in visually perturbed gait initiation. *Gait and Posture*, *58*, 268–273. https://doi.org/10.1016/j.gaitpost.2017.08.013

Wang, Y., & Srinivasan, M. (2014). Stepping in the direction of the fall: The next foot placement can be predicted from current upper body state in steady-state walking. *Biology Letters*, *10*(9). https://doi.org/10.1098/rsbl.2014.0405

Wispinski, N. J., Gallivan, J. P., & Chapman, C. S. (2020). Models, movements, and minds: bridging the gap between decision making and action. In *Annals of the New York Academy of Sciences* (Vol. 1464, Issue 1, pp. 30–51). John Wiley and Sons Inc. https://doi.org/10.1111/nyas.13973

Wong, A. L., & Haith, A. M. (2017). Motor planning flexibly optimizes performance under uncertainty about task goals. *Nature Communications*, *8*. https://doi.org/10.1038/ncomms14624

Xie, L., & Wang, J. (2019). Anticipatory and compensatory postural adjustments in response to loading perturbation of unknown magnitude. *Experimental Brain Research*, *237*(1), 173–180. https://doi.org/10.1007/s00221-018-5397-x

Yamada, H., & Shinya, M. (2021). Variability in the Center of Mass State During Initiation of Accurate Forward Step Aimed at Targets of Different Sizes. *Frontiers in Sports and Active Living*, *3*. https://doi.org/10.3389/fspor.2021.691307