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Research article

Postural adjustment in standing position when catching a ball under unpredictable conditions of the direction to be caught

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A R T I C L E I N F O

Keywords:
Ball-catching
Sudden postural perturbation
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Compensatory and anticipatory adjustments
Postural control

A B S T R A C T

Background: Balanced postural control of the body is associated with two mechanisms: anticipatory postural adjustment and compensatory postural adjustment. Previous studies reported changes in body postural control under unpredictable conditions (interference with closed eyes).
Research question: To ascertain whether in contrast with predictable disturbances, there is a difference in muscle activity and center of pressure displacement changes when the direction of the disturbance is unpredictable.
Methods: Three examiners stood at 45° to the left, the front, and 45° to the right of the participant to throw the ball to him. 11 healthy young participants were required to maintain their balance in the standing position after receiving the ball in conditions with and without known catching directions. The anticipatory postural adjustment and compensatory postural adjustment integral changes of the muscle activity in the lower limbs and trunk bilaterally and at the center of pressure displacement in the known and unknown conditions were observed. Two-way ANOVA was used to compare the differences in muscle activity and displacement changes.
Results: Results showed that the center of pressure in the anticipatory postural adjustment and compensatory postural adjustment in the posterior direction with known catching direction was significantly shorter than those without. Integration of electromyogram in anticipatory postural adjustment of the right soleus ($p = 0.023$) was associated with higher muscle activities in the unknown than known conditions. Integration of electromyogram in compensatory postural adjustment of the right tibial anterior ($p = 0.004$), right rectus femoris ($p = 0.023$) and left rectus abdominis ($p = 0.038$) in unknown catching direction had significantly greater muscle activity than those without. When the direction of the perturbation is unpredictable, the central nervous system may initiate and induce greater center of pressure changes in the posterior direction with changes in several muscular activities to ensure postural control.

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1. Introduction

In daily lives, our postural adjustment is often lost due to disturbances from the external environment. Therefore, postural control is an important factor in preventing falls. However, postural adjustment requires a complex interaction between the musculoskeletal and nervous systems (motor, sensory, and cognitive systems) [1]. To preserve the equilibrium, the central nervous system (CNS) uses two types of alterations in the trunk and leg muscle activities. The first type of conditioning is an anticipatory postural adjustment (APA) [2], indicating that body will show predictive muscle activity before the disturbance to ensure proper return of the body posture. The second type of adjustment is a compensatory postural adjustment (CPA) [3,4] defined as the activation of muscles to regulate balance after the occurrence of imbalance. Postural muscle activation and balance recovery mechanisms are combined for postural recovery. In addition to the amount of muscle activity used to determine the muscular ability that regulates posture, displacement by the center of pressure (COP) on the sole is also used in previous studies to respond to the body's ability to balance. In the upright, state against external balance disturbance, greater COP displacement changes also indicate greater physical instability [5].

APA is an important neuromuscular biomarker that can be used to assess the degree of impairment in balance, and the risk of falls [6]. If the APA is impaired, older may have a higher risk of falling because their balance is more unstable compared to the younger [7]. Consequently, ball throwing and catching exercises are often performed to improve the balance and coordination abilities of the upper and lower limbs in patients with movement disorders and older [8]. Additionally, throwing exercises strengthened the body's APA and enhanced postural stability in older individuals [9,10]. Some previous studies have investigated the APA and CPA based on muscle activity when throwing and catching balls in unstable conditions, such as in foam mats and trampolines. The ankle, thigh, and trunk APA and CPA were activated when catching the ball [11]. Findings in muscle activity before catching the ball were as follows: compared to the rigid floor, the tibialis anterior activation was greater during the trampoline condition, whereas the soleus muscle inhibition was higher during the foam cushion condition [12].

An accurate estimation of perturbations is required to adequately prepare for postural control [13]. However, in daily life, postural perturbations are not always fully predictable. A previous study demonstrated that closed-eye unpredictable perturbations caused greater APA activity than the open-eye predictable perturbations when physical perturbations were triggered [14]. Moreover, the lumbar muscles are activated earlier when the weight of the object is unknown than in conditions when the weight is known [15].

In daily life, the direction of external disturbances is usually unpredictable. Imagine if there was a difference between the mechanisms of posture control when we face to predictable disturbances compared to when we face disturbances in unpredictable directions. There was insufficient research to see if there is a more significant clinical effect of ball-catching training modalities with unknown directional interference to improve balance ability. Also, there was no study explaining how APA and CPA affect postural control when the direction of the disturbance is unknown. The mechanism of achieving the postural adjustment is based on the muscle activity and COP changes under the condition in an unknown disturbance direction. Therefore, the current study primarily aimed to simulate the situation in daily life when a disturbance in an unknown direction occurs and observe the APA and CPA of the lower extremities and trunk muscles, as well as a difference in the COP with participants when the direction of the examiner's throw was predictable and unpredictable. Secondly, the effect of ball-catching under different orientations on the muscles on both sides of the body will be observed. I hypothesized that the APA and CPA activities would have greater muscle activity to ensure body balance when the direction of ball throwing is unknown than known. Similarly, the displacement change in the COP would be greater under unknown conditions, appearing to cause greater perturbation and more unstable postural. Regarding the difference in the magnitude of muscular activity on both sides of the body depending on the direction of the catch, I hypothesized a difference in muscle activation on both sides of the body in different catching directions. A better understanding of the response of postural control when the direction of the disturbance is unknown, and the APA, and CPA during these tasks, will be important to support and improve therapeutic interventions based on balance exercises.

2. Methods

2.1. Participants

11 (5 male and 6 female) participants recruited for this experiment were students from Tohoku University. The average (standard deviation) age, height, and weight of participants were 27.1 (7.1) years, 168 (8.1) cm, and 63.1 (13.8) kg, respectively. All of them were in good health, anyone with a history of orthopedic problems, neurological disorders, musculoskeletal disorders, or any other

Table 1
Participant demographics.

Characteristics	Value
Age (years)	27.1 ± 7.1
Height (cm)	168 ± 8.1
Body Mass (kg)	63.1 ± 13.8
Female/Male (n)	5/6
Leg dominance L/R (n)	0/11
Orthopedic problems, neurological diseases, or musculoskeletal disorders (n)	0

Values are mean ± SD, n.

condition that might interfere with task performance was excluded and participants were identified as right-footed. Participant demographics are presented in Table 1. All participants understood the purpose and experimental procedure before conducting this study, and their consent was obtained and signed. This study was approved by the ethical committee of the Tohoku University Graduate School of Medicine (approval number: 2020-1-1138).

2.2. Procedure

All participants were required to fill out a record sheet of personal information before participating in the experiment, including age, height, weight, left and right footedness, and exercise habits. To determine the dominant foot, participants were examined using the Revised Waterloo Footedness Questionnaire [16]. The experimental task was the ball-catching movement. Participants were exposed to postural perturbations generated by catching medicine balls (mass = 1.0 kg). Before each experiment, the participants practiced the ball-catching task according to the experimental procedure. In the experiment, three examiners stood at 45° to the left of the participant, at 45° to the right of the participant, and directly in front of the participant (Fig. 1). A previous study showed that when the perturbation occurs in the 45° direction of the body, muscle activities in the APA occur in the trunk muscles (rectus abdominis (RA), external oblique, internal oblique, and transversus abdominis) in the corresponding direction [17]. The distance from each examiner to the subject was equal and determined by the subject's height. (e.g., if the height of the subject was 170 cm, then the distance between the three examiners and the subject was 170 cm) [12].

The experiment consisted of two prediction conditions: predictable and unpredictable directions from which the ball would come and 15 random ball-catching tasks in each condition. The examiner threw the ball into the participant's hands based on the order of the random number table. The ball was thrown five times from each direction, each condition occurred a total of 15 times in 3 directions, left, front and right, for a total of 30 ball-catching tasks for two conditions. There was a 2-min break between each of the five ball-catching tasks. In the predictable direction, the participant was verbally instructed on the direction of the ball being thrown (e.g., left, right, and front) before each throw. Conversely, in the unpredictable direction condition, the participant was not told of the direction in which the ball was to be thrown. In all tasks, subjects were asked to keep their eyes forward during the catching task.

The participant maintained a standing posture with both feet shoulder-width apart, upper limbs at 40° shoulder flexion, elbow flexion at 90°, and the wrist joint in the middle position during measurement (Fig. 2). The positions of three examiners were changed for each participant to reduce the effects of each examiner's throwing habits on the experiment. To control the speed of the ball and the strength of the checker's throw, three examiners threw the ball at the same height and make the same preparatory throwing motion and threw the ball at the same time to ensure the strength of the throw and the speed of the ball.

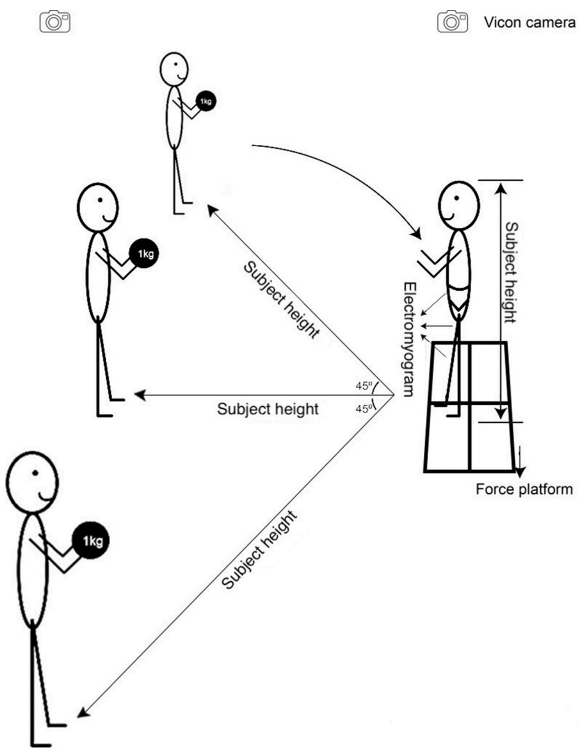

Fig. 1. Location of participant and examiner. Three examiners stood directly in front, left in front, and right in front of the subject. The distance between the subject and the examiner was determined by the subject's height.

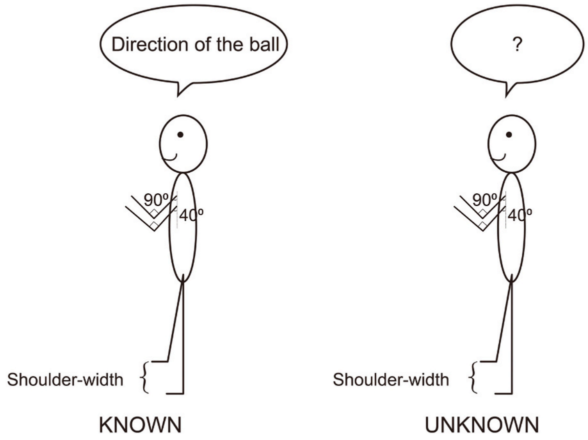

Fig. 2. Subjects' standing position. The experimental conditions were divided into known and unknown catch directions for the subjects. The subject kept the shoulder joint flexed at 40° and the elbow joint flexed at 90° to receive the ball.

2.3. Instrumentation

A three-dimensional motion analysis system at 120 Hz (MAC 3D, Motion Analysis Corporation, CA, USA, 2010) with an 8-camera setup and four 90 × 60-cm ground reaction force plates (Anima Corporation, Tokyo, Japan, 2007) at a sampling frequency of 1200 Hz was used to measure the ball-catching movement. 25 reflective markers with a 19-mm diameter were attached to the following landmarks of the trunk and lower limbs using an adhesive tape: the anterior and posterior sides of the left and right heads, right and left acromion, seventh cervical spinous process, tenth thoracic spinous process, xiphoid process, cervical incision, inferior angle of the right scapula, right and left superior anterior iliac spines, right and left superior posterior iliac spines, right and left greater trochanter, right and left lateral epicondyles, right and left external capsule, right and left calcaneal ridges, and right and left fifth metatarsals. Further, four markers were attached to each ball used to record the trajectory and movement speed of each ball.

The surface electromyography (EMG) (WEB-1000, NIHON KOHDEN Corporation, Tokyo, Japan, 2007) was used to measure muscle activity in the trunk and lower extremities during the ball-catching task. The skin was disinfected with a 75% concentration of alcohol before applying the surface electrodes (ZB-150H, NIHON KODGEN Corporation, Tokyo, Japan, 2007). Surface electrodes were placed on the following muscles in the trunk and lower extremities as recommended by the SENIAM for sensor locations: soleus (2/3 of the line between the medial condyles of the femur to the medial malleolus), tibialis anterior (1/3 of the line between the tip of the fibula and the lateral malleolus), biceps femoris (50% of the line between the ischial tuberosity and lateral epicondyle of the tibia), rectus femoris (RF) (50% of the line from the anterior spina iliaca superior to the superior part of the patella), RA (2-cm superior and 1-cm lateral to the umbilicus), and erector spinae muscles (2 finger-widths lateral of the spinous process of L1) [18,19].

2.4. Data processing

All data for this experiment were synchronized and smoothed using the motion analysis software Cortex (Motion Analysis Corporation, USA). Marker data, the COP data, and EMG data were analyzed using KineAnalyzer (KISSEI COMTEC Co. LTD., Japan). Marker and COP data were filtered with a cutoff frequency of 7 Hz and 20 Hz using a low-pass Butterworth filter, and EMG data were bandpass filtered (10–500 Hz). The reflective markers on the body are mainly used to confirm the ball-catching movement and the catching direction. The markers on medicine balls are used to calculate the speed of the ball. When the value of the curve suddenly becomes 0, indicating that the participant catches the ball so that its speed suddenly becomes zero. This point was defined as the instantaneous time point of ball catching (T0). The period from −500 ms to −450 ms in T0 was defined as the baseline. The period from −100 ms to −50 ms in T0 was defined as the APA period [2,20], whereas the period from −50 ms to +200 ms in T0 was defined as the CPA period [21,22].

2.4.1. Analysis of muscle activity

First, the integrated EMG (IEMG) was calculated for each muscle in the baseline during the ball-catching task as the baseline of each muscle activity. IEMG in each muscle during the ball-catching task was calculated in APA and CPA periods and was normalized by IEMG during the baseline. The IEMG of each muscle during both APA and CPA periods were calculated using the following equation [23,24]:

$$IEMG_{APA\ (CPA)} = \frac{a - 3b}{3b}$$

In this equation, a denotes the IEMG during the APA or CPA period and b denotes the IEMG at baseline. $IEMG_{APA}$ period lasts from −100 to 50 ms; the $IEMG_{CPA}$ period lasts from 50 to 200 ms, whereas the baseline period lasts from −500 to −450 ms in T0 (Fig. 3).

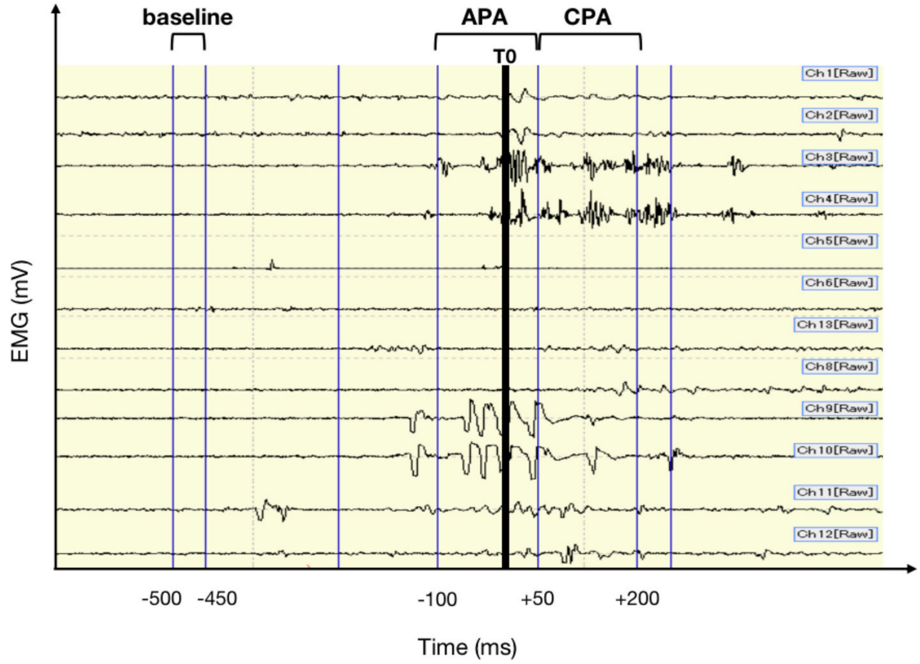

Fig. 3. Analysis of electromyography. The figure represents the electromyography data in the calf, thigh, and abdominal back muscles. There were 12 EMG changes during the ball-catching task, where the black vertical line in the figure indicates the moment of catching the ball (T0). The periods of baseline, anticipatory postural adjustment (APA), and compensatory postural adjustment (CPA) were defined as the time interval from −500 ms to −450 ms, from −100 ms to +50 ms, and from +50 ms to +200 ms with respect to T0, respectively. Ch1, left soleus; Ch2, right soleus; CH3, left tibialis anterior; CH4, right tibialis anterior, CH5, left biceps femoris; CH6, right biceps femoris; CH7, left rectus femoris; CH8, right rectus femoris; CH9, left rectus abdominis; CH10, right rectus abdominis; CH11, left erector spinae; CH12, right erector spinae.

2.4.2. COP analysis

The average value and standard deviation of the COP displacements from −500 to −450 ms were calculated as a baseline. The value obtained by subtracting the baseline of the COP displacement from the COP displacement at T0 was defined as COP_{APA}. The value of the maximum COP displacement during the CPA period minus the baseline COP displacement was defined as COP_{CPA} [25,26] (Fig. 4). Then, the COP displacement in both anteroposterior and lateral directions was analyzed.

2.4.3. Statistics

The required sample size was calculated using the G*power3 for two-way ANOVA prior to subject recruitment. The effect size, according to Cohen [27], the effect sizes were defined as small, d = 0.2, median, d = 0.5, and large, d = 0.8 or above. Therefore, based on within-subject factors: two prediction conditions – known and unknown; three directions – left, front, right, and 0.4 for the effect size, 0.05 for the significance level, and 0.8 for the power it was calculated that 11 subjects were needed [28]. Reference was also made to previous studies in which 10 subjects were required to detect statistically significant differences between EMG and COP in different conditions with 80% power and 95% of confidence.

All data were statistically analyzed using the statistical analysis software SPSS version 26 (IBM Corporation, USA). The dependent variables were analyzed by descriptive statistics and the normality of the assessed data was tested using the Shapiro-Wilk test, and since most of the data conformed to a normal distribution [29]. Therefore, the mean and standard deviation of each data were calculated separately for each prediction condition in each direction using a two-way ANOVA of variance to compare the $IEMG_{APA}$, $IEMG_{CPA}$, COP_{APA}, and COP_{CPA}. First, the parameters of each muscle divided into three directions (left front right) were tested with the main and interaction effect, respectively. Then tests of between-subjects effects were performed for each parameter. The post-hoc testing was corrected using the Bonferroni method. When a significant main effect of the direction is observed, the multiple comparison test was conducted to compare variables among directions. Furthermore, when interaction effects were statistically significant, post hoc tests were conducted to compare variables among three directions in each prediction condition and to compare variables between prediction conditions for each direction. For all tests, the threshold for statistical significance was set at $p < 0.05$.

3. Results

3.1. Muscle activity and COP displacement under predicted conditions

Tables 2 and 3 show the comparisons of $IEMG_{APA}$, $IEMG_{CPA,}$ COP_{APA} and COP_{CPA} between known and unknown conditions during

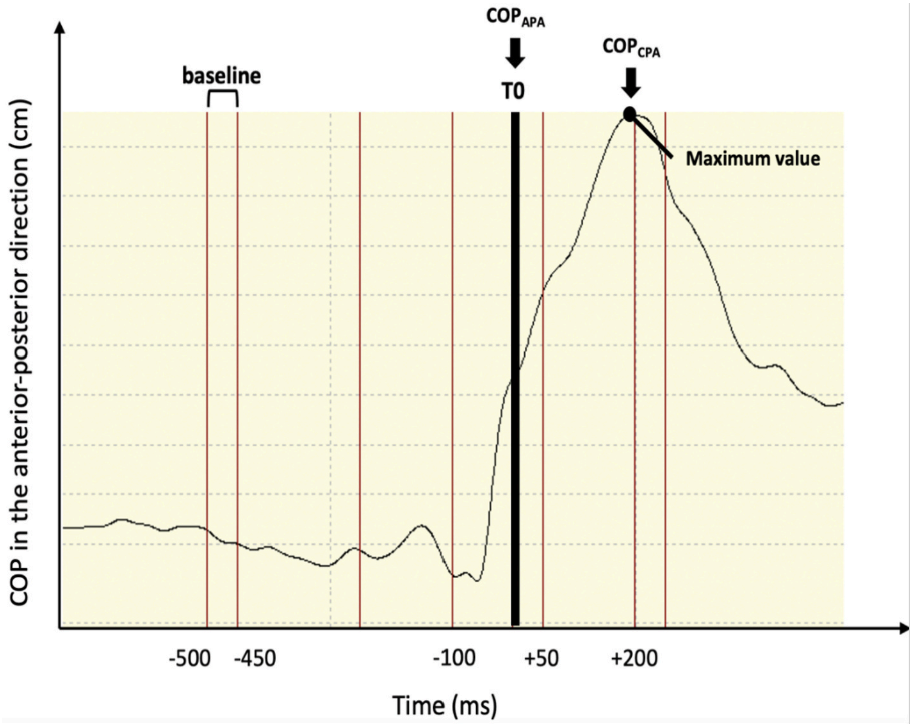

Fig. 4. Analysis of center of pressure. The displacement of center of pressure (COP) in the anterior-posterior direction during the ball-catching task. The bold black line indicates the instantaneous time of the ball catch (T0). The displacement of the COP at T0 is noted as COP_{APA}. The maximum COP displacement during compensatory postural adjustments (CPA) is noted as COP_{CPA}. Positive values indicate movement in the posterior direction, and negative values indicate movement in the anterior direction.

the ball-catching task. Positive values in the table represent muscle activity, whereas negative values represent activation of antagonist muscle. The main effect of the prediction in the COP_{APA} ($p = 0.039$) and COP_{CPA} ($p = 0.049$) in the anteroposterior direction was observed. Compared to the direction of the catch that could be predicted, the COP displacement changed more during the CPA and APA periods in unknown conditions. Furthermore, Table 4 showed a significant interaction ($p = 0.023$) was observed in the $IEMG_{APA}$ of the right soleus, but no significant difference was found in the $IEMG_{APA}$ of the right soleus between prediction conditions and among directions. In multiple comparisons of post-hoc testing, it was observed that the muscle activity in $IEMG_{APA}$ of the right soleus muscle showed more obvious activation when catching the ball on the right side than on the left side in known conditions ($p = 0.044$).

Table 2
The integrated electromyography ratios of the calf, thigh, and abdominal back muscles and the center of pressure displacement during the anticipatory postural adjustment in the known and unknown conditions.

Muscles	Prediction		*p*-value
	Known	Unknown	Main effect
	(mean ± SD)	(mean ± SD)	Prediction
Left soleus	0.05 ± 0.15	0.02 ± 0.11	0.332
Right soleus	−0.03 ± 0.13	−0.03 ± 0.17	0.939
Left tibialis anterior	0.25 ± 0.40	0.69 ± 1.09	0.085
Right tibialis anterior	0.24 ± 0.31	0.49 ± 0.81	0.193
Left biceps femoris	0.02 ± 0.04	0.04 ± 0.07	0.161
Right biceps femoris	0.19 ± 0.33	0.14 ± 0.30	0.491
Left rectus femoris	0.04 ± 0.09	0.17 ± 0.28	0.081
Right rectus femoris	0.04 ± 0.12	0.14 ± 0.22	0.086
Left rectus abdominis	0.22 ± 0.50	0.43 ± 0.77	0.309
Right rectus abdominis	0.08 ± 0.12	0.46 ± 1.15	0.128
Left erector spinae	0.57 ± 0.71	0.75 ± 2.09	0.594
Right erector spinae	0.59 ± 0.56	0.56 ± 0.52	0.837
Displacement direction	(mean ± SD, cm)	(mean ± SD, cm)	
Anterior-posterior[a]	0.78 ± 0.87	1.03 ± 0.71	0.039
Left-right	−0.07 ± 0.99	−0.15 ± 0.50	0.712

[a] Significantly different from predicted conditions at $p < 0.05$.

Table 3
The integrated electromyography ratios of the calf, thigh, and abdominal back muscles and the center of pressure displacement during the compensatory postural adjustment in known and unknown conditions.

Muscles	Prediction		*p*-value
	Known	Unknown	Main effect
	(mean ± SD)	(mean ± SD)	Prediction
Left soleus	−0.01 ± 0.14	0.03 ± 0.12	0.182
Right soleus	−0.02 ± 0.18	−0.04 ± 0.20	0.608
Left tibialis anterior	0.50 ± 0.76	1.09 ± 1.28	0.063
Right tibialis anterior[a]	0.51 ± 0.70	0.97 ± 0.86	0.004
Left biceps femoris	0.07 ± 0.12	0.09 ± 0.21	0.635
Right biceps femoris	0.34 ± 0.39	0.33 ± 0.44	0.957
Left rectus femoris	0.13 ± 0.22	0.32 ± 0.45	0.083
Right rectus femoris[a]	0.11 ± 0.26	0.36 ± 0.35	0.023
Left rectus abdominis[a]	0.38 ± 0.81	0.61 ± 1.12	0.038
Right rectus abdominis	0.31 ± 0.69	0.68 ± 1.17	0.080
Left erector spinae	1.23 ± 2.36	1.18 ± 2.74	0.652
Right erector spinae	1.17 ± 1.07	1.14 ± 1.04	0.816
Displacement direction	(mean ± SD, cm)	(mean ± SD, cm)	
Anterior-posterior[a]	1.43 ± 0.85	1.93 ± 0.77	0.049
Left-right	−0.23 ± 1.28	−0.08 ± 1.38	0.099

[a] Significantly different from predicted conditions at $p < 0.05$. SD: standard deviation.

Table 4
The integrated electromyography ratios of the right soleus muscle during the anticipatory postural adjustment in three directions under the known and unknown conditions.

Muscles	Direction	Prediction		*p*-value		
		Known	Unknown	Main effect		Interaction
		(mean ± SD)	(mean ± SD)	Prediction	Direction	
Right soleus[a]	Left	0.03 ± 0.07	−0.06 ± 0.16	0.939	0.732	0.023
	Front	0.00 ± 0.09[b]	−0.04 ± 0.16			
	Right	−0.10 ± 0.17	0.02 ± 0.20			
	Total	−0.26 ± 0.13	−0.29 ± 0.17			

[a] An interaction effect was significant in direction and prediction conditions at $p < 0.05$. SD: standard deviation.
[b] R-SOL interaction was significant $p < 0.05$ in the condition of direction and prediction, and in the post-hoc tests there was a significant difference between the left and right directions in the known condition $p < 0.05$.

However, the main and interaction effects of TA, RF, RA, BF, and ES during APA were not significant in the direction and predicted conditions. Conversely, a significant main effect of the prediction condition was observed in the $IEMG_{CPA}$ of the right tibialis anterior ($p = 0.004$), right RF ($p = 0.023$), and left RA ($p = 0.038$). The $IEMG_{CPA}$ of the right tibialis anterior, right RF, and left RA was significantly larger in the unknown condition than those in the known condition. Nevertheless, the main and interaction effects of SOL, BF, and ES were not significant in the direction and predicted conditions during CPA.

3.2. *Muscle activity and COP displacement under direction conditions*

Comparisons of $IEMG_{APA}$, $IEMG_{CPA}$, COP_{APA} and COP_{CPA} between the three different directions during the ball-catching task are shown in Tables 5 and 6. No significant main effects of the direction were observed in the $IEMG_{APA}$ and $IEMG_{CPA}$ ($p > 0.05$) in tests of between-subjects effects. Furthermore, the main effects of the COP_{APA} ($p = 0.011$) and COP_{CPA} ($p < 0.001$) were observed in the left-right direction. Pairwise comparisons in post-hoc tests revealed that the COP_{APA} in the left-side condition more significantly deviated to the right side than that in the right-side condition ($p = 0.040$). In the CPA period, the COP displacement in the left (right) condition more significantly deviated to the right (left) side than in the right (left) and front conditions (left vs. right, $p < 0.001$; left vs. front, $p < 0.001$; front vs. right, $p = 0.001$). In other words, the COP_{APA} and COP_{CPA} in the same lateral throwing direction were larger than those in the different lateral direction.

4. Discussion

Differences in the APA and CPA of the body muscle activities and the COP displacement between the conditions with and without known catching direction among three catching directions were examined. The hypothesis that the TA and RF and RA muscular activity in CPA would be greater, and the COP changes in APA and CPA would be greater, under conditions where the catching direction in unknown conditions was supported by the results. A previous study has confirmed that the muscles catching objects under closed-

Table 5
The integrated electromyography ratios of the calf, thigh, and abdominal back muscles and the center of pressure displacement during the anticipatory postural adjustment in three directions conditions.

Muscles	Direction			*p*-value
	Left	Front	Right	Main effect
	(mean ± SD)	(mean ± SD)	(mean ± SD)	Direction
Left soleus	0.02 ± 0.13	0.04 ± 0.15	0.04 ± 0.11	0.840
Right soleus	−0.01 ± 0.13	−0.02 ± 0.13	−0.04 ± 0.19	0.732
Left tibialis anterior	0.60 ± 0.88	0.44 ± 0.92	0.37 ± 0.76	0.361
Right tibialis anterior	0.39 ± 0.71	0.36 ± 0.66	0.33 ± 0.52	0.735
Left biceps femoris	0.04 ± 0.06	0.02 ± 0.04	0.02 ± 0.06	0.530
Right biceps femoris	0.09 ± 0.33	0.22 ± 0.21	0.18 ± 0.38	0.441
Left rectus femoris	0.14 ± 0.34	0.10 ± 0.12	0.09 ± 0.13	0.606
Right rectus femoris	0.13 ± 0.25	0.09 ± 0.13	0.04 ± 0.14	0.247
Left rectus abdominis	0.21 ± 0.38	0.54 ± 1.00	0.23 ± 0.33	0.114
Right rectus abdominis	0.11 ± 0.12	0.46 ± 1.40	0.24 ± 0.36	0.407
Left erector spinae	0.38 ± 0.56	1.09 ± 2.50	0.51 ± 0.78	0.430
Right erector spinae	0.55 ± 0.56	0.62 ± 0.53	0.56 ± 0.55	0.842
Displacement direction	(mean ± SD, cm)	(mean ± SD, cm)	(mean ± SD, cm)	
Anterior-posterior	0.95 ± 0.61	1.03 ± 1.01	0.74 ± 0.73	0.362
Left-right[a]	0.07 ± 0.40	0.04 ± 1.05	−0.46 ± 0.66	0.011

[a] Significant difference between left and right directions at $p < 0.05$. SD: standard deviation.

eye conditions (unknown) have greater CPA activity than under open-eye conditions (known) [13]. In addition, a new finding was that when external interference direction was unpredictable, the muscle conditioning ability of the dominant side was greater than that of the non-dominant side, which likewise indicated the laterality of the muscle in catching the ball under different directions.

The SOL muscle on the right side tends to be activated when throwing the ball from the right direction with known catching direction, as compared to without both in APA and CPA. Muscle inhibition occurred because the COP moved in a backward direction when a perturbation of the catching task occurred, and SOL were activated as an antagonist muscle to return to the COP in a more forward position [30]. The following three reasons were considered to obtain such results: first, when the balance was unstable, the recovery of the catching posture control was mainly controlled by the ankle joint. Second, the CNS will regulate the distal muscles (SOL) to control balance during APA [12]. Third, when faced with a sudden disturbance coming towards the body, the postural control ability on the dominant side of the body will be stronger than that of the non-dominant side. In other words, because the dominant side of the subjects in this experiment was the right side, the muscle control ability of the right SOL would be more significant than that of the left side [31].

Observing the muscle CPA activity revealed that TA, RF, and RA had greater activity under unknown than known conditions. This is also consistent with the results of previous studies [13], thereby suggesting that after the posture is broken, the unknown condition may require greater CPA muscle activity to ensure body balance. These results occurred because when the body was cognitively unable to judge the catching direction, the CNS perceived the body to be more unstable based on the direction of the known catch; therefore, more CPA activity was mobilized to bring the body back in balance. In contrast to other studies, this experiment measured the muscular activity on both sides of the body. Based on these results, a significant difference was observed between the TA, RF of the right, and the RA of the left in conditions where the catching direction was known and unknown. By ensuring that participants in this experiment were all right-footed, such results may be related to the greater conditioning of the dominant foot muscles. In a previous study, compared to the non-dominant side, the muscles on the dominant side showed a more pronounced adjustment ability [31].

Regarding muscle activation for postural control in general, in the face of a sudden onset of disturbance, the SOL muscles react preferentially to maintain body balance during the expected phase, because the ankle joint reaction occurred first when the body's balance was about to be broken [30]. Then, during the compensatory phase, the TA, RF and RA will stimulate more activation activities to restore the balance of the body broken by the catching action. However, the absence of significant results for the biceps femoris and erector spinae muscles were probably since the BF and ES were not overly involved in an external disturbance event such as a ball-catching. Because the ball was coming at the body from the anterior direction, the TA, BF and RA may be more involved in activation. Certainly, in other studies, significant activity of the erector spinae muscles was observed during the CPA phase when a weight was dropped vertically onto a tray held in the hand [15]. Therefore, in these experimental results, it was speculated that the significant results may be because the subjects caught the ball in the anterior-posterior direction and did not use the erector spinae and biceps femoris muscles excessively.

Changes in the APA and CPA of the COP in the backward direction were speculated to be greater in unknown ball-catching direction. This agrees with those of previous studies where COP changes were greater in unknown conditions [32,33]. The greater the APA changes of the COP before disrupting the body equilibrium, the more unstable the postural equilibrium. Changes in displacement in the lateral direction of the COP have not been investigated in previous studies, and because the present experiment involved a task catching a ball thrown from the left and right sides, COP changes in the left-right direction were analyzed. Greater COP changes in the same lateral throwing direction were found compared to in the different lateral directions both in APA and CPA. However, no significant difference was observed between known and unknown conditions. Additionally, participants catching the ball on the left side had a more rightward COP displacement based on the frontal- and right-side catching. Conversely, COP displacement changes would

Table 6
The integrated electromyography ratios of the calf, thigh, and abdominal back muscles and the center of pressure displacement during the compensatory postural adjustment in three directions conditions.

Muscles	Direction			*p*-value
	Left	Front	Right	Main effect
	(mean ± SD)	(mean ± SD)	(mean ± SD)	Direction
Left soleus	−0.02 ± 0.14	0.02 ± 0.12	0.03 ± 0.14	0.366
Right soleus	0.02 ± 0.18	−0.05 ± 0.17	−0.07 ± 0.21	0.069
Left tibialis anterior	0.92 ± 1.20	0.60 ± 0.96	0.88 ± 1.11	0.237
Right tibialis anterior	0.87 ± 0.66	0.65 ± 0.75	0.69 ± 1.00	0.476
Left biceps femoris	0.09 ± 0.20	0.08 ± 0.18	0.06 ± 0.12	0.714
Right biceps femoris	0.36 ± 0.49	0.35 ± 0.26	0.30 ± 0.46	0.899
Left rectus femoris	0.30 ± 0.52	0.24 ± 0.31	0.15 ± 0.18	0.256
Right rectus femoris	0.26 ± 0.38	0.23 ± 0.30	0.22 ± 0.32	0.929
Left rectus abdominis	0.44 ± 0.79	0.45 ± 0.82	0.60 ± 0.32	0.578
Right rectus abdominis	0.40 ± 0.66	0.37 ± 0.55	0.72 ± 1.44	0.550
Left erector spinae	1.51 ± 2.84	1.31 ± 3.24	0.80 ± 1.05	0.546
Right erector spinae	1.16 ± 1.05	1.00 ± 0.95	1.30 ± 1.16	0.479
Displacement direction	(mean ± SD, cm)	(mean ± SD, cm)	(mean ± SD, cm)	
Anterior-posterior	1.79 ± 0.75	1.80 ± 0.94	1.45 ± 0.83	0.081
Left-right[a,b,c]	1.20 ± 0.54	0.00 ± 0.00	−1.65 ± 0.91	<0.001

[a] Significant difference between left and right directions at $p < 0.001$.
[b] Significant difference between left and front directions at $p < 0.001$.
[c] Significant difference between right and front directions at $p < 0.001$. SD: standard deviation.

be greater to the left when participants caught the ball on the right side compared to the front and left sides. When the body is faced with interference from different directions, the body may ensure the body's balance in advance by changing the COP displacement in the opposite direction to the interference direction.

In previous studies, the effect of vision on postural control had been demonstrated, with body balance being more unstable when the eyes are closed [13]. A relationship between visual influence and postural control was also confirmed in this study, where visual information is first generated in the visual cortex and then transmitted to the supplementary motor cortex (SMA). Experiments also using arm lifts in clinical trials had demonstrated that APA is associated with the SMA area [34]. Neuronal signals are then transmitted from the SMA to the spinal cord, through which they are transmitted to the muscles to stimulate anticipatory and compensatory postural adjustments. Thus, inadequate visual information probably accounts for the differences in posture control in the predicted conditions. In addition, training strengthens the APA regulation [12]. Therefore, individuals with high levels of exercise in daily life will produce less APA activity in the face of unknown perturbations, and smaller changes in COP displacement represent more stable postural control. In addition, the focus of this experiment was to observe the postural control of the abdomen, back and lower limbs, so the influence of interference on the upper limbs was not observed. But more significant APA was observed for the unknown condition (eyes closed) in other body disturbance studies (bumping into the shoulder to cause a disturbance), so it is hypothesized that postural control of the upper extremities would be consistent with the body stem when the direction of the disturbance is unknown [13].

Regarding the less significant differences of muscle activity in this experiment, Some limitations were considered. First, because it was necessary to ensure that the subjects could not predict the direction of the catch, the speed of the ball was not accurately controlled. However, the height, distance, and throwing motion were the same among the three examiners. Moreover, the three examiners were asked to practice throwing the ball before the experiment to ensure that the ball speed was as similar as possible. Second, the subjects were healthy young adults, who then had better balance when faced with the catching task, so there was no significant difference in the face of known and unknown experimental conditions, speculating that perhaps the effect would be greater in older adults performing the same assignment.

Finally, this study demonstrates that performing a ball-catching task when the direction of the interference is unknown leads to more significant results in terms of muscle activity. Positive results were obtained in a safe study with healthy subjects, therefore the same ball-catching task perhaps has application in the clinical setting to increase patient postural control of the muscles to improve balance ability.

5. Conclusion

COP_{APA} and COP_{CPA} in the posterior direction in known catching direction was significantly shorter than unknown. $IEMG_{APA}$ of the soleus on the right side with unknown catching direction tended to be more significant than that without. $IEMG_{CPA}$ of the TA and RF on the right side and RA on the left side in unknown catching direction was significantly larger than that without. When the perturbation direction is unpredictable, the CNS may initiate and induce greater COP changes in the posterior direction with changes of several muscles activities to ensure body balance in the anteroposterior direction. This will first activate SOL activity during the anticipatory phase to reduce external disturbances to homeostasis, and then the compensatory phase to mobilize muscle activity in TA, RF, and RA to restore the equilibrium may initiate and induce greater COP changes in the posterior direction to ensure body balance in the anteroposterior direction. However, we did not observe significant results for TA, RF, RA, BF, and ES during APA, as well as for BF and

ES during CPA in the direction and predicted conditions. It was speculated that this may be since the activity of ball-catching causes only a small portion of postural control-related muscle activity. For other postural control-related muscles, by contrast, the activation was not significant. Evidence was provided for the effectiveness of this experiment in increasing the effectiveness of rehabilitative balance intervention training.

Author contribution statement

Wenyu Zhang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Yusuke Sekiguchi: Conceived and designed the experiments.

Keita Honda: Analyzed and interpreted the data.

Shi-Ichi Izumi: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

Conflict of interest

None.

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