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Effect of Visual Input and Foam Rubber on Leg-Joint Angles and Sway of Center of Pressure during Stepping on the Spot

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Abstract

Dynamic balance has frequently been evaluated by using center of pressure (COP) during stepping movement. COP sway may be greater during stepping on foam rubber, which is a kind of external load. This study aimed to examine the effect of leg-joint angles and COP sway during stepping on a spot in 13 young male adults (mean age 25.6 ± 4.8 years, mean height 170.6 ± 5.2 cm, mean mass 69.1 ± 8.2 kg), with or without foam rubber and with eyes open or closed. When subjects stepped on foam rubber placed on two force plates (right and left), while matching a tempo of 100 bpm for 20 s under the above four conditions, characteristics such as mean angles of hip, knee, and ankle joints and COP sway were measured. In the results of two-way ANOVA (rubber condition × eye condition) and post-hoc tests, the hip-joint angle was significantly greater with eyes open, regardless of with or without foam rubber. The knee-joint angle was significantly greater in eyes closed with off-foam-rubber than on-foam-rubber. The ankle-joint angle was significantly greater in off-foam-rubber, regardless of eyes open or closed, and with eyes open than with eyes closed, regardless of with or without foam rubber. The total trace length and velocity were significantly greater in off-foam-rubber with eyes open, and on-foam-rubber with eyes closed than on-foam-rubber with eyes open. The other sway parameters were significantly greater with eyes open than with eyes closed regardless of with or without foam rubber. The hip-joint angle was significantly greater with eyes open regardless of with or without foam rubber. In conclusion, the COP sway during stepping with a stipulated tempo is less with eyes open than eyes closed, but the motion of knee and ankle joints is greater with eyes open. The sway distance and velocity during stepping with eyes open and motion of knee and ankle joints during stepping with eyes closed are both affected by the foam-rubber load. When stepping on the foam rubber, movement of the knee joints relates to distance and velocity of COP regardless of open or closed eyes. The findings in this study will be used to evaluate balance functions that are closely related to basic movements.

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Keywords

Dynamic Balance, Step, Young

1. Introduction

Dynamic balance contributes to the achievement of fundamental human movements such as walking, running, standing up, etc. It has been assessed by tests such as the Timed "Up & Go" test (Podsiadlo & Richardson, 1991) and the Sit-to-Stand (Yamada & Demura, 2004). Recently, a dynamic balance test using a stepping movement, which resembled gait motion, was developed by Shin & Demura (2007). This test, which assesses dynamic balance from step number or contact time of feet within a certain time, demands that subjects support the whole body on one leg because they are stepping with both legs alternately. Additionally Shin & Demura (2009) developed a test evaluating dynamic balance based on errors between stipulated tempo and contact time of feet during stepping on the spot. Because of its very easy motion, the stepping test is useful for assessing dynamic balance in people of all ages. On the other hand, balance has also been evaluated by sway of center of pressure (COP) to disturbance loads (Baloh et al., 1998). According to Fujimoto et al. (2010), sway velocity and area, which were important indexes of COP sway, increased during static standing on foam rubber. Although Aoki et al. (2012) examined COP sway during stepping on the spot, presumably, COP sway and leg motion became greater because the subjects' felt that their feet were unstable when stepping on foam rubber.

On the other hand, people normally maintain a collapsing posture by integrating vestibular, visuosensory, and somatosensory information from the central nervous system (Demura et al., 2005). Among the three sensory systems, the visual system is the most important input for human postural stability, and a decline of visual function largely affects postural control (Paulus et al., 1984). According to Masani et al. (2007), differences in COP sway between eyes open and closed during static upright stance were found in the elderly but not in the young. However, COP sway and stepping movement (leg-joint angles) may differ among eye conditions, even in young people, because the support base changes largely due to standing on one leg during stepping. Until now, the foam-rubber-load test has mainly been used to detect defects in patients' vestibular systems. Presumably, when subjects stepped on foam rubber in a state of disturbed bathyesthesia and intercepted sight input (eyes closed), owing to the fact that stable posture depended mainly on a labyrinthine system, COP sway and stepping movement were greatly affected, as compared to stepping on a flat floor with eyes open. Aoki et al. (2012) reported that COP sway differed only minutely among those under 60 during stepping, regardless of whether their eyes were open or closed. However, a larger COP sway was found in 80-year-olds than in 70-year-olds with eyes open, and in 70-year-olds than in those under 60 with eyes closed. Thus, age-specific differences in COP sway during stepping with stipulated tempo with open and closed eyes have been determined. Additionally, COP sway during stepping with stipulated tempo under sight restriction and disturbance of somatosensor input has been examined.

This study examined the effect of leg-joint angles and COP sway during stepping on a spot considering four conditions: with and without foam rubber and with eyes open and closed.

2. Methods

2.1. Subjects

Thirteen young, male adults (age: 25.6 ± 4.8, range: 20 - 35 years) participated in this study. The subjects were healthy and confirmed not to have disorders or otitis media. Prior to the experiment, we explained in detail its purpose and procedures, and obtained their informed written consent. They were all judged to be right-handed by a dominant-hand survey developed by Demura (2012). The Kanazawa University Health & Science Ethics Committee approved this experimental protocol (Approval number: 2012-03).

2.2. Experimental Equipment and Methods

2.2.1. Equipment

During stepping, the subject's leg-joint angles were recorded and analyzed with a motion-analysis system, LOCUS MA (ANIMA, Japan). This system can calculate the distance and height of 16 joint markers in a subject's entire body. It uses a three-video-camera setup, and after calculating joint angles from joint markers at three points, records them on three-dimensional coordinates. Scans were performed by setting up the three video cameras in front of the subjects.

A stabilometer (G620, Anima, Japan) was used to measure the center of pressure (COP) during stepping. This machine calculates COP of vertical loads from the values of three vertical load sensors located at the corners of an isosceles triangle on a leveled surface. Data was sampled at 100.0 Hz and transferred to a personal computer following A/D conversion.

The foam rubber (ANIMA, Japan) (thickness, 3.5 cm; tension strength, 2.1 kg/cm^2; density, 0.06 g/cm^2; stretch rate, 110%) used in the test deforms according to weight distribution because its materials resemble a soft cushion. Thus, participants do not have a flat support base and find it difficult to maintain stable posture. The foam rubber can be placed on a G620 without any type of attachment.

2.2.2. Study Methods

Prior to the experiments, a tester attached 16 infrared-light-emitting markers on the participants' anatomical landmarks (both sides acrominon, cubitus, hand joint, iliac crest, great trochanter, knee joint, ankle joint, and metatarsal bone). Participants were instructed to place one foot on a right plate and the other on a left plate. They stood with their arms hanging loosely by their sides and gazed at the visual target in front of them with their eyes open and then eyes closed. Next, participants stepped 40 times (20 times on each side) in a rhythm of 100 bpm to the beeping of a metronome. The stepping task was performed once with foam rubber and once without it. The measurement order was random. Each test was performed with a 2-min rest period.For the "with" test, the foam rubber was set on a COP measurement plate.

2.3. Parameters

Each joint angle was calculated from respective angles connecting the following three points: iliac crest, great trochanter, and knee joint for hip joint; great trochanter, knee joint and ankle joint for knee joint; and knee joint, ankle joint and metatarsal bone joint for ankle joint. A mean of the angle calculations during stepping for 20 s was used as kinematic parameter.

The following evaluation parameters of the center of gravity were selected: total trace length (the full length that COP moved during stepping); velocity (mean velocity); circumference (medial area surrounded by circumference of a trace of COP sway); rectangular area (bounded by front-back circumference and horizontal direction of sway); left-right width (greatest deflection [three-dimensional coordinate] distance); and front-back width (greatest deflection distance). When these have a large variation, postural control ability is evaluated to be inferior (Aoki et al., 2012). Each COP parameter was calculated by the load values from both COP plates.

2.4. Data Analysis

Mean differences of joint angles and COP sway parameters for each condition were tested by two-way ANOVA for repeated measures (foam rubber × eyes). When a significant interaction or main effect was found, a Tukey's Honestly Significant Difference (HSD) test was used for multiple comparisons. Effect size (ES) was calculated to examine the size of difference. Pearson's correlations were calculated to examine relationships between joint-angle parameters and COP parameters. The significant statistical level was set at 5%.

3. Results

Table 1 shows the basic statistics for foam rubber (on or off) and eyes (open or closed), the results of two-way ANOVA (foam rubber and eyes), and multiple comparisons for hip-, knee-, and ankle-joint angles. Significant main effect (eyes) was found in hip-joint angle: it was greater with eyes open than with eyes closed. Significant interaction was found in the knee-joint angle: it was greater in off-foam-rubber than in on-foam-rubber, although the difference was small (ES: 0.03). Significant main effect in both main effects (foam rubber and eyes) was found in ankle-joint angle: it was greater in off-foam-rubber than in on-foam-rubber and greater with eyes open than with eyes closed (ES: 0.17 - 0.30).

Table 2 shows the basic statistics for foam rubber (on or off) and eyes (open or closed), the results of two-way ANOVA (foam rubber and eyes), and multiple comparisons for COP sway parameters. Significant interactions were found in total trace length and velocity, greater in off-foam-rubber with eyes open and on-foam rubber with eyes closed than in on-foam rubber with eyes open (ES: 0.78 - 0.89). Significant main effect for the eyes factor was found in the other parameters: they were greater with eyes closed than with eyes open, regardless of with or without foam rubber (ES: 0.64 - 1.08).

Table 3 shows the correlations between joint-angle parameters and COP parameters. Knee-joint angle during stepping on foam rubber showed significant and high correlations (r = 0.65 - 0.78) with COP parameters, except front-back width with eyes open, and total trace length and velocity with eyes closed.

4. Discussion

Hip- and ankle-joint angles were greater with eyes open than with eyes closed, regardless of with or without foam rubber. According to Ishida et al. (2010), the maximum ankle-joint angle was greater with eyes open than with eyes closed when subjects performed physical anteversio and rehabilitation movements. On the other hand, Buckley et al. (2008) reported that ankle-joint plantar flexion during on-off movement of feet during walking was greater with eyes closed than in normal vision state. From these results, Buckley et al. (2008) inferred that subjects use caution, checking the ground with a lead leg. Although we used stepping movement in this study, the ankle-joint angle was greater with eyes open than with eyes closed, following the result of Ishida et al. (2010). Jones et al. (2006) reported that the ankle-joint angle is affected by stand height when subjects step down from a

Table 1. Basic statistics for each ankle-joint angle and results of two-way ANOVA and multiple comparisons.

		Open (A)		Close (B)		F-value			
		Mean	SD	Mean	SD	F1	F2	F3	Post-hoc
Hip joint	off (1)	132.9	9.9	131.6	12.1	0.29	6.70*	0.03	
	on (2)	132.3	9.4	131.3	9.5				
Knee joint	off (1)	154.0	3.7	154.8	4.3	6.75*	0.45	4.93*	B1 > B2
	on (2)	153.3	4.0	153.0	4.4				
Ankle joint	off (1)	110.5	5.1	109.3	5.1	28.65*	20.77*	0.21	
	on (2)	109.0	5.0	108.1	5.3				

*$p < 0.05$, Open: eyes open. Closed: eyes closed. Off: load off. On: load on. A1: load off and eyes open. A2: load on and eyes open. B1: load off and eyes closed. B2: load on and eyes closed. F1: main effect (load on-off). F2: main effect (eyes open–closed). F3: interaction.

Table 2. Basic statistics of COP parameters, results of two-way ANOVA, and multiple comparisons.

		open (A)		close (B)		F-value			
		Mean	SD	Mean	SD	F1	F2	F3	Post-hoc
Total trace length (cm)	off (1)	1054.0	108.4	1060.7	93.6	1.98	16.26*	6.47*	A1, B1, B2 > A2
	on (2)	965.7	117.6	1050.9	122.8				
Velocity (cm/sec)	off (1)	43.0	4.4	43.4	3.7	2.70	12.15*	4.78*	A1, B1, B2 > A2
	on (2)	39.7	4.5	42.1	4.8				
Circurmference (cm^2)	off (1)	144.3	35.5	165.8	31.7	0.22	37.39*	1.83	
	on (2)	137.7	32.6	181.9	47.6				
Rectangular area (cm^2)	off (1)	247.5	47.7	289.8	41.1	0.19	22.41*	1.24	
	on (2)	238.8	57.7	312.5	82.1				
Left-right width (cm)	off (1)	21.1	2.3	22.5	1.9	1.53	30.84*	1.84	
	on (2)	21.6	2.7	23.8	3.3				
Front-back width (cm)	off (1)	11.7	1.8	12.9	1.1	0.53	13.12*	0.66	
	on (2)	11.0	1.6	13.0	2.5				

*$p < 0.05$, Open: eyes open. Close: eyes close. Off: load off. On: Load on. A1: Load off and eyes open. A2: Load on and eyes open. B1: Load off and eyes close. B2: Load on and eyes close. F1: main effect (load on-off). F2: main effect (eye open-close). F3: interaction.

Table 3. Correlations between joint-angle parameters and COP parameters.

		Total trace length	Velocity	Circumference	Rectangular area	Left-right width	Front-back width
Off a rubber with open eyes	Hip joint angle	0.11	0.09	−0.04	−0.04	−0.09	0.03
	Knee joint angle	−0.36	−0.36	0.06	−0.07	−0.40	0.15
	Ankle joint angle	−0.19	−0.20	0.05	−0.03	0.03	−0.11
Off a rubber with close eyes	Hip joint angle	0.23	0.23	−0.20	−0.26	−0.12	−0.30
	Knee joint angle	−0.37	−0.34	−0.09	−0.13	−0.32	0.10
	Ankle joint angle	0.01	−0.04	0.34	0.26	0.21	0.22
On a rubber with open eyes	Hip joint angle	−0.34	−0.36	−0.29	−0.32	−0.44	−0.09
	Knee joint angle	−0.66*	−0.65*	−0.78*	−0.65*	−0.73*	−0.39
	Ankle joint angle	0.30	0.33	0.16	0.27	0.08	0.40
On a rubber with close eyes	Hip joint angle	−0.39	−0.46	−0.41	−0.38	−0.44	−0.18
	Knee joint angle	−0.67*	−0.73*	−0.24	−0.22	−0.55	0.09
	Ankle joint angle	0.08	0.27	0.04	0.01	0.08	−0.06

*$p < 0.05$.

stand. Even for the young, it is not easy to perform step movement on the unstable foam rubber with closed eyes. Presumably in the case of closed-eyes, intercepted vision information, since subjects find it difficult to perform a dynamic step with stable posture, their ankle-joint angle lessens in order to match tempo with low toe height without raising the foot high.

In addition, both knee- and ankle-joint angles were greater in off-foam-rubber than in on-foam-rubber with eyes closed. When stepping on foam rubber with eyes closed, it appears that participants performed a small step movement without extending the knee joint greatly and by fixing an ankle joint to maintain postural stability. Furthermore, participants appeared to use a strategy that inhibits excessive extension of each leg-joint angle with eyes closed or when in an unstable posture due to foam-rubber load. Four COP parameters (total trace length, circumference, left-right width, and front-back width) were greater with eyes closed than with eyes open, regardless of with or without foam rubber (ES: 0.64 - 1.08). Humans maintain a collapsing posture normally by integrating vestibular, visuosensory, and somatosensory information from the central nervous system (Demura et al., 2005). Among these three senses, visuosensory plays the most important role. When sight information was intercepted by closed eyes, posture control depended on vestibular and somatosensory information. The present results suggest that for leg-joint angles, eyes closed compared with eyes open affects step movement performed while maintaining stable posture. The four parameters above concern area and amplitude, which evaluate the sway size of COP (Kitabayashi et al., 2002). The COP sway during one-leg standing is considered greater with eyes open than with eyes closed.

On the other hand, COP parameters of length and velocity evaluate total distance and the speed of sway during stepping. Results on foam rubber were the same as the above four sway parameters for on foam rubber, but they were greater with eyes open in off-foam-rubber than in on-form-rubber (off-foam-rubber > on-foam-rubber). In short, only in the eyes-open state were these parameters affected by the foam-rubber load. Although dynamic stepping was difficult for participants due to intercepted vision information (closed eyes), with open eyes, the possible effect of foam rubber became marked. The present results suggest that subjects land on and off feet relatively quickly, without lifting them high, due to maintaining stable posture during one-leg standing with eyes closed. The above may be understood also from the point that COP sway (except for distance and velocity) was less with eyes open than with eyes closed (sway becomes less with eyes closed due to landing quickly).

Among leg joints, only the knee-joint angle showed relationships with the five COP parameters, except for front–back width with eyes open, and with total trace length and velocity with eyes closed during stepping on foam rubber (r = −0.67 to −0.73). Presumably knee joints play an important role on the unstable foam rubber; movement of knee-joint function during stepping with eyes open affects many body sway parameters. From the present results, it appears that when stepping on unstable foam rubber, subjects step while attempting to maintain stable posture. Thus, subjects use a strategy of keeping knee angles small, and what is reported above affects step movement and also COP sway.

The collapsing posture is normally maintained by integration of vestibular, visuosensory, and somatosensory information from the central nervous system (Demura et al., 2005). Aoki et al. (2012) reported that 80-year-olds, unlike those of other age levels, have different body sway movements during stepping with eyes open and eyes closed. This study examined the effect of sight restriction and disturbance load on COP sway during stepping with stipulated tempo, and confirmed that sway distance and velocity during stepping with eyes open and the motion of knee and ankle joints during stepping with eyes closed are affected by the rubber load. The findings in this study will serve as a basic document for balance function evaluation.

5. Conclusion

COP sway during stepping with a stipulated tempo is less with eyes open than with eyes closed, but the motion of knee and ankle joints is greater with eyes open. The sway distance and velocity during stepping with eyes open and the motion of knee and ankle joints during stepping with eyes closed are both affected by the foam-rubber load. When stepping on foam rubber, movement of the knee joints relates to distance and velocity of COP regardless of open or closed eyes.

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