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Age-Related Differences in Coupling of Toe and Center of Pressure during the One-Legged Stance

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Abstract

This study aimed to investigate the characteristics of the coupling of the center of pressure (COP) movement and toes in older adults during one-legged standing (OLS). Participants were community dwelling older and younger adults. Toe vertical force during the OLS was recorded using a plantar-pressure distribution system, and the vertical forces in the hallux, little toe, and the first and fifth metatarsophalangeal (MP) joints were analyzed. A cross-correlation function was performed to examine the coordination between toes and between COP movement and four regions of the foot. The cross-correlation functions showed no significant difference in coefficients between toes. The OLS duration in the older adults was significantly correlated with the coefficient between the medial-lateral component of the COP and the first MP region. This study suggests that it is important to press the first MP region appropriately relative to COP movement to maintain the OLS.

Keywords

One-Legged Stance, Coordination, Coupling, Toe, Older

1. Introduction

Improved balancing ability is closely associated with enhanced functional independence measurement scores at acute rehabilitation stages [1] and at later life stages in older adults [2]. However, maintaining balance by controlling body posture is a complex process in which multiple subsystems and environmental factors interact to prevent one from falling [3]. The one-legged stance (OLS) test is frequently used for assessing the balance of individuals with various disorders

[4] [5] [6] [7]. For older adults, the ability to maintain the OLS is an important indicator of their balancing ability, and it can be used to predict the risk of hip-fractures [8] and falls—those with a history of falls have a shorter OLS duration [9]. Although most studies regarding the OLS have considered duration as a variable, it is important in a rehabilitation situation to clarify how physical function is associated with the ability to maintain the OLS.

Jonsson *et al.* [10] examined differences between younger and older adults in the time course of the center of pressure (COP) during the OLS. They found that medial-lateral (ML) variability in the COP at 1 second after lifting a foot is larger in older adults. Mani *et al.* [11] examined distance between the COP and center of mass (COM) during the OLS, and reported that OLS duration was associated with the distance just after leg-lifting. These previous studies suggested that, for OLS duration, it is important to adjust posture before the steady phase in the OLS.

However, in clinical situations, we have observed that older adults who fell followed a larger sway during steady phase in the OLS. This means that impaired postural adjustments not only just after leg-lifting but also while maintaining the OLS cause falls. Furthermore, in the steady phase, we believe that COP control ability is associated with maintaining the OLS duration. While maintaining the OLS, individuals move the COP relative to COM movement [12] [13]. The COP position is adjusted by joint movement of the foot [14], that is, toe coordination. Thus, to examine COP control mechanisms, which are conducted by toe coordination, while maintaining the OLS, we need to examine the roles of the foot, including the toes, during that time. Tanaka *et al.* [15] found that the peak pressure value of the hallux was correlated with the sway amplitude in the anterior-posterior direction during a dynamic OLS. Although this finding suggests the importance of the hallux for maintaining the OLS, it did not examine toe coordination or coupling between the toe and COP fluctuation. Moreover, there has been no report examining differences between younger and older adults in coordination and coupling, although it is well known that ankle strategy becomes poor with aging [3] [16].

In the present study, we aimed to clarify differences between younger and older adults in the coordination of toes and coupling between toe and COP movement. We hypothesized that toe coordination, that is, coordination between hallux and little toe, in older adults would be poorer than that in younger adults as muscle strength in the toes attenuates with aging [17], which is a risk factor for falls [18]. Moreover, we hypothesized that this attenuation would cause poor coupling between the toe and COP in older adults as compared to younger adults.

2. Materials and Methods

2.1. Participants

Seventeen community dwelling older adults (mean age (±standard deviation:

STD) = 76.4 ± 6.1 years; male = 7; female = 10) were recruited from a cohort enrolled for medical examinations in Kimobetsu, Japan. The inclusion criteria were as follows: no neurological disorder (including diabetes), no physical injury, and no medical history within the preceding year, no severe foot deformation, no pain in their foot, right leg dominance [19], and capable of maintaining the OLS for over 3 s. They could walk independently and did not perform periodic exercise. Leg dominance was determined based on the leg used for kicking a ball [11] [20]. For the younger adult group, we recruited 19 university students (mean age (±STD) = 21.2 ± 0.4 years; male = 9, female = 10). They were all healthy (no medical history) and had experienced no physical ailments within the preceding year. Their anthropometrical characteristics are shown in **Table 1**. All procedures performed in this study involving human participants were approved by the committee of Hokkaido University of Science in Sapporo, Japan (No. 193) and in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Participants read a description of the basic procedures of the experiments and provided written informed consent.

2.2. Measures

Plantar-pressure Distribution System

Vertical forces for each toe and metatarsophalangeal (MP) joint during the OLS were recorded using a plantar-pressure distribution system (600 mm × 600 mm, MD-1000, ANIMA, Tokyo, Japan [21]). The sampling frequency was set at 100 Hz. There were sensors every 10 mm^2 of the mat (3600 sensors in total); each had a resolution of 1 N and recorded vertical force in every contact region. We calculated the COP position at time points using the vertical forces reported by each sensor in the software for the plantar-pressure distribution system.

2.3. Procedures

Both the younger and older participants stood barefoot, using their left leg as the

Table 1. Participants' characteristics.

	Younger	Older	*p* value
N	M: 9, F: 10	M: 7, F: 10	0.709
Age (years)	21.2 (0.4)	76.4 (6.1)	<0.001
Height (m)	1.63 (0.07)	1.54 (0.08)	0.001
Mass (kg)	59.5 (13.0)	56.3 (11.7)	0.447
Foot length (cm)	23.1(1.9)	23.0 (1.3)	0.811
Foot width (cm)	9.2 (1.1)	8.5 (0.9)	0.051
Hallux length (cm)	6.2 (0.7)	6.2 (0.6)	0.770
Little length (cm)	3.9 (0.4)	4.1 (0.6)	0.183
Distance navicular-MP (cm)	8.4 (0.9)	8.1 (0.6)	0.253

Note: Values represent means (standard deviations). N: Chi-squared test was performed. Other characteristics: non-paired t-test was performed.

supporting leg [11], and stared at a circle positioned at their eye level at a distance of 2 m from their lateral malleolus. The left leg was the non-dominant leg in all participants, and was used as the support leg because of the high possibility of injuries when a non-dominant leg is used as a support leg [22]. A few practice trials followed by a 5 min break were permitted prior to the test. Participants stood on a mat featuring a plantar-pressure distribution system, with feet shoulder-width apart. Each participant crossed his or her arms in front of their chest. The left navicular bone was set as the x-axis (the midpoint of the anterior-posterior [AP] edges of the mat), while the long axis of the left foot (from the second toe to the midpoint of the calcaneus bone) was set as the y-axis (the midpoint of the ML edges of the mat) (**Figure 1**). We instructed the participants to maintain the OLS for as long as possible, and when no longer able, to immediately lower their right foot. An examiner stood by to support participants when they started falling over. Each participant started the OLS at their own time and performed at least three OLS trials. The upper limit was set at 30 s [23] [24] [25]. We analyzed trials that were maintained for over 3 s. We measured the length of the left hallux and little toe and the distance between the left navicular and the first MP joint, which helped to analyze the vertical force in each region.

2.4. Data and Statistical Analysis

The vertical forces recorded by each sensor and the COP coordinates (x and y) at each time point were converted into ASCII files for analysis. As behavior before

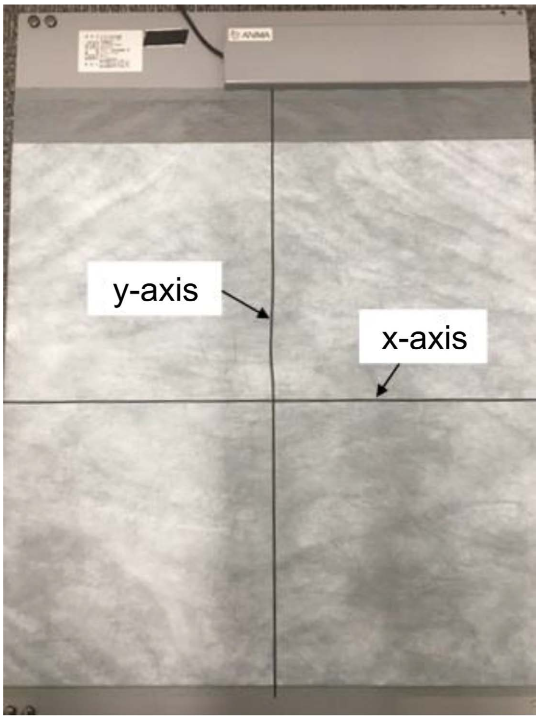

Figure 1. Plantar-pressure distribution system. The x-axis line was placed at the midpoint of the anterior-posterior [AP] edges of the mat. The y-axis line was placed at the midpoint of the ML edges of the mat.

the steady phase affects the OLS duration [10] [11], we analyzed data from 1 s after task commencement. The time of commencement was set as the time when the force, registered by a sensor under the right foot, fell to zero.

For trials below 30 s, we analyzed all data up to the point when the right foot contacted the mat, or until the position of the left foot changed. The period just before the right foot touched the mat presented different states with maintaining periods, resulting from an unstable COP sway. Therefore, we divided trials into two phases: stable (maintaining) and unstable (1 s before stopping the OLS). In order to confirm whether the present result was similar to previous literature, using each component (AP [COP_{ap}] and ML [COP_{ml}]) of the COP, we calculated root mean square (RMS) [26] and mean velocity (MV) [27] [28]. The high sensitivity of the MV effect in regard to detecting abnormalities has been previously reported [29] [30]. Furthermore, we calculated the mean position of each component (AP_{mean} and ML_{mean}) of the COP relative to the origin (intersection of the x- and y-axes on the mat) during the OLS. **Figure 2** shows an analysis image of

		0	0.108	0.112	0.154	0	0.253	0.267	0
0	0	0.276	0.576	0.153	0.108	0.12	0.487	1.488	0.184
0	0.5	0.589	0.197	0.1	0	0.104	0.385	1.585	0.152
0	0.365	0.225	0.172	0.233	0.267	0.248	0.401	0.348	0
0.219	0.297	0.31	0.496	0.815	1.032	0.755	1.044	0.453	0
0.169	0.624	0.905	1.294	2.072	1.653	1.399	1.495	0.978	0
0.216	1.594	1.126	1.509	1.697	1.168	1.272	2.326	1.059	0
0.399	2.212	1.435	1.101	0.721	0.469	0.592	0.787	0.184	0
0.228	1.801	1.533	0.908	0.361	0.134	0.152	0.106	0	0
0	1.473	1.257	0.729	0.139	0	0	0	0	
0	0.746	1.198	0.503	0	0	0	0		
0	0.327	1.176	0.45	0	0	0	0		
0	0.18	1.293	0.542	0	0	0	0		
0	0	0.931	0.655	0.12	0	0	0		
	0	0.44	0.722	0.233	0	0	0		
	0	0.245	0.822	0.575	0.189	0	0		
	0	0.173	0.807	0.841	0.785	0.125	0		
	0	0.164	0.98	1.233	1.36	0.404	0		
	0	0.162	1.282	1.456	1.655	0.822	0		
	0	0.154	1.418	1.968	1.999	1.032	0		
	0	0	1.345	2.117	2.297	0.755	0		
	0	0	0.469	1.486	1.325	0.233	0		
	0	0	0	0.134	0.114	0	0		

Figure 2. Plantar distribution output for a young participant.

plantar-pressure distribution at a certain time point. Using the distance between the left navicular and the first MP joint and the length of the hallux and little toe, we identified regions of the hallux, the little toe, and the first and fifth MP joints (colored red, green, yellow, and blue, respectively, in **Figure 2**) for each participant. These regions were selected as both of these ends are key in controlling the COP in the medio-lateral direction. Moreover, we examined both toes and MP joints as in our experience, MP regions compensate for toe impairment in clinical situations.

The vertical forces in each region were values summed from four sensors (two = length, two = breadth) around the identified regions, which were based on the foot anthropometric measurement such as distance between navicular and MP, hallux and little toe lengths, and foot width (**Table 1**). The number of sensors for each region matched the size of the little toe. Examples of the time course of each region for one older participant are shown in **Figure 3**.

Coordination between the regions as well as the coupling between each component of the COP (COP_{ap} and COP_{ml}) and each region were elucidated using

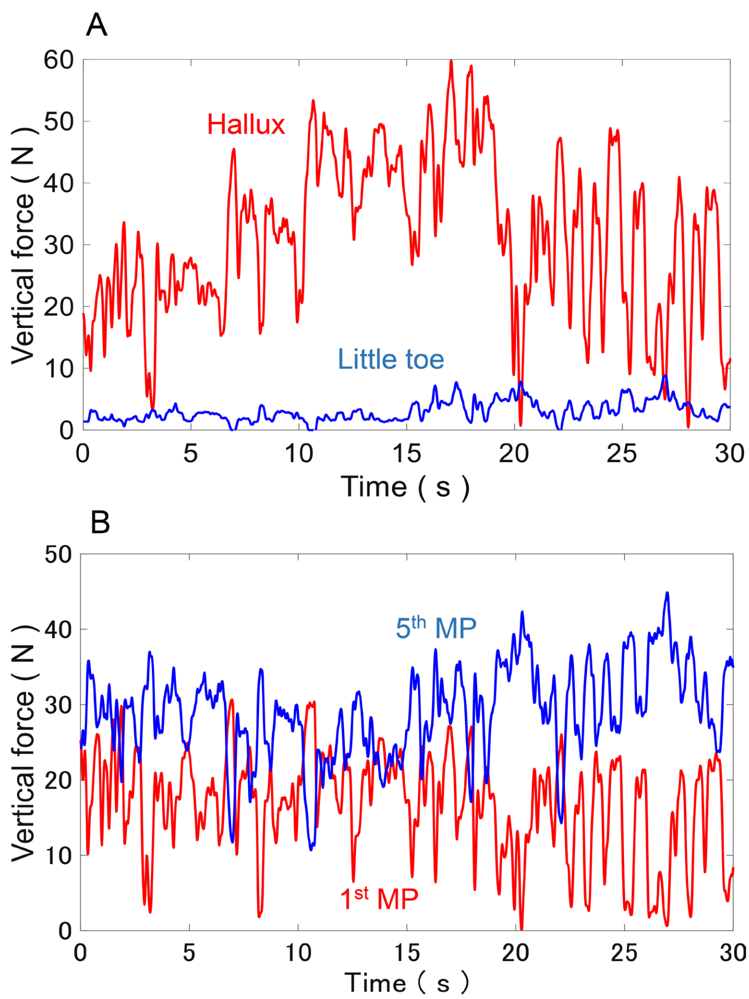

Figure 3. Time course of vertical force in each region (hallux [A-red], little toe [A-blue], first MP joint [B-red], and fifth MP joint [B-blue]) during an older adult's OLS.

the cross-correlation function [31] [32]. Based on this function, correlation coefficients and lags between each region and each COP component were identified. The cross-correlation function was applied to the following 10 parameters: 1) Toes (hallux and little toe); 2) First and fifth MP joints; 3) COP_{ap} and hallux; 4) COP_{ap} and little toe; 5) COP_{ap} and first MP joint; 6) COP_{ap} and fifth MP joint; 7) COP_{ml} and hallux; 8) COP_{ml} and little toe; 9) COP_{ml} and first MP joint; 10) COP_{ml} and fifth MP joint. Control of COP occurs because of the appropriate push of foot joints such as the hallux, little toe, and MPs on the floor relative to COP movement. Therefore, phase lags were used to clarify whether older adults used each foot region with appropriate timing relative to COP movement compared with younger adults. For the trials shorter than 30 s, coefficients and lags in both the stable and unstable phases were calculated. The exported data were analyzed using the MATLAB software (Mathworks, MA, USA).

We examined the normal distribution of variables regarding the COP (MV, RMS, and position of the COP) using the Shapiro-Wilk test. Among the sway parameters for the older adults, the MV_{ap}, RMS_{ap}, and RMS_{ml} showed no normal distribution, and the Mann-Whitney test was performed to examine differences between the older and younger participants. Since the AP_{mean} and ML_{mean} showed normal distribution in both groups, a non-paired t-test was performed for those. The test was also applied to examine the OLS duration in the two age groups. The coefficients and lags between toes and between MP joints were examined using a non-paired t-test. Furthermore, we performed a two-way analysis of variance (ANOVA; factors: age and region) to study the differences in trends of coefficients and lags in the first (hallux and first MP) and fifth (little toe and fifth MP) rays (definition of "ray", e.g., Oatis [14]), relative to each component of the COP. A post hoc analysis was performed as the interaction in the ANOVA was significant. As the variables of the factors (age and regions) were two, a non-paired and a paired t-tests were performed for the factor of age and region, respectively, as the post-hoc analysis. Then, we compared the younger and older adults' stable phase values. Trials lasting less than 30 s among the older participants were compared for coefficients and lags between the unstable and stable phases using a paired t-test. A Pearson's product moment correlation was performed to examine the relationship between the OLS duration and each coupling variable (foot regions relative to COP components) [11]. The level of statistical significance was set at $p < 0.05$. The effect size was calculated using r [33] and η^2 for t-test and ANOVA, respectively. All statistical analyses were performed using SPSS version 20.0 (IBM Corporation, Armonk, NY, USA).

3. Results

Figure 4 shows the time course of the COP and the vertical force on each region for both the older and younger groups. The OLS durations for all younger participants were 30 s, which was the upper limit. Contrarily, the average (*STD*) duration for the older participants was 19.5 s (±11.2 s), which was significantly

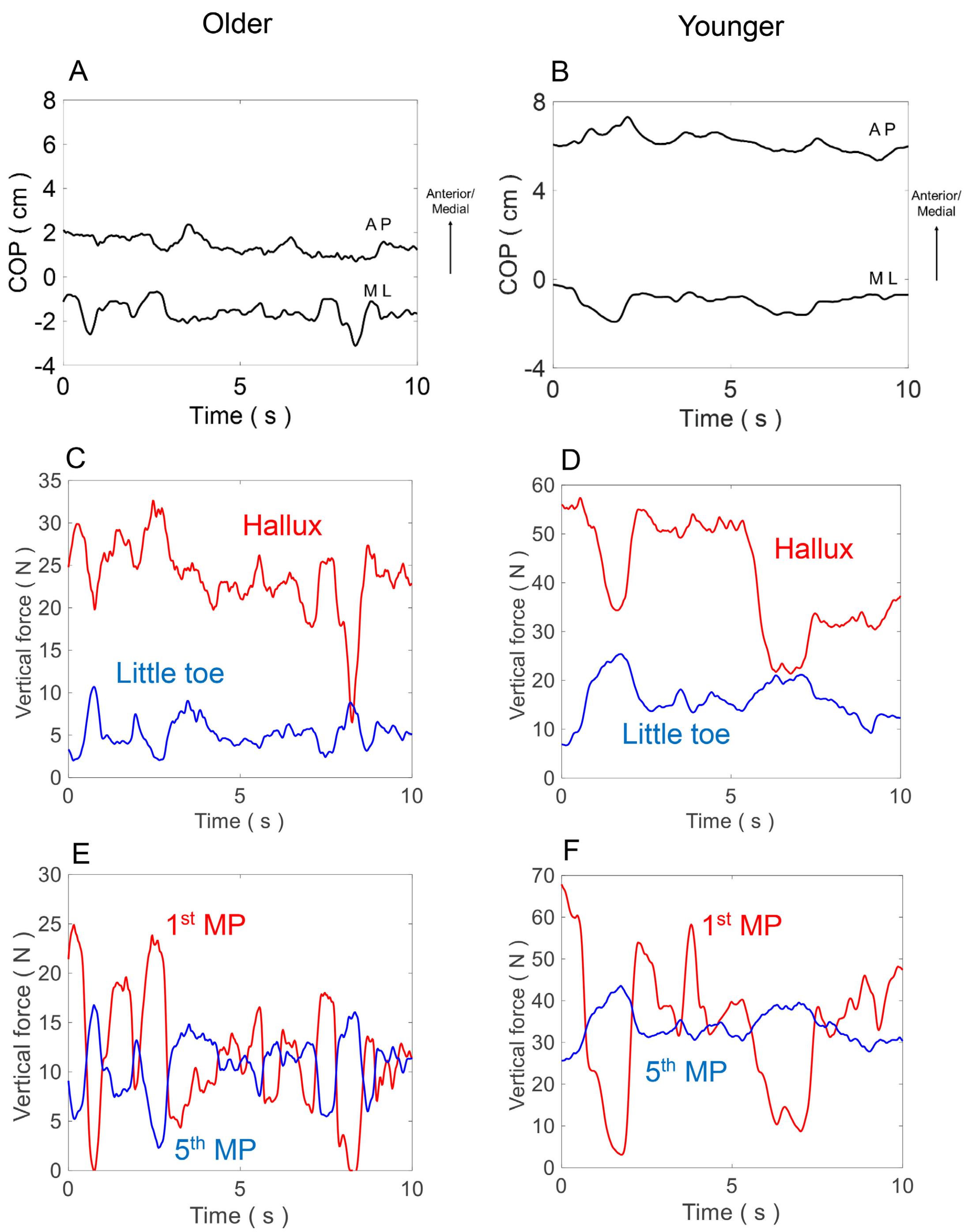

Figure 4. Time course of the COP and vertical force in each region over 10 s for both older (A, C, and E) and younger (B, D, and F) participants. (A and B) AP and ML component of the COP position, (C and D) hallux and little toe, (E and F) first and fifth MP joints, respectively.

shorter than that of the younger group (t = −4.07, $df = 34$, $p < 0.001$, $r = 0.57$). The number of older participants who lasted less than 30 s was 10 (mean = 12.1 s). Table 2 shows results of the COP parameters. The older group showed significantly faster MV_{ap} and MV_{ml} than the younger group (both $p < 0.001$). For RMS, RMS_{ap} did not differ significantly between groups, whereas the older participants

Table 2. Parameters of the COP in the younger and older participants.

	Younger (n = 19)			Older (n = 17)			p value
	25% tile	50% tile	75% tile	25% tile	50% tile	75% tile	
MV_{ap} (mm/s)	15.42	18.75	20.96	37.57	52.24	59.99	<0.001
MV_{ml} (mm/s)	37.28	40.23	43.55	60.87	72.07	84.27	<0.001
RMS_{ap} (mm)	3.10	3.68	4.04	4.16	4.74	5.50	0.274
RMS_{ml} (mm)	4.69	6.16	7.93	5.01	6.79	9.31	0.001
	Mean		S.E.	Mean		S.E.	
AP_{mean} (mm)	4.78		0.67	−0.02		0.57	<0.001
ML_{mean} (mm)	−0.90		0.10	−0.47		0.62	0.509

50 percentile = median, S.E.: standard error. MV: mean velocity, RMS: root mean square, AP: antero-posterior, ML: medio-lateral, AP_{mean}: mean position of COP_{ap} (plus indicated anterior), ML_{mean}: mean position of COP_{ml} (plus indicated medial).

showed significantly larger RMS_{ml} ($p < 0.001$). The position of the AP_{mean} (Figure 4(A) and Figure 4(B)) in the older group was significantly more posterior compared to the younger group (t = −5.19, df = 34, $p < 0.001$, r = 0.68); there was no significant difference between the groups regarding the position of the ML_{mean}.

Similarly, neither the cross-correlation coefficients for the toes and MP joints (Figure 5(A)), nor the lag in both the toes and the MP joints (Figure 5(B)) were significantly different between groups. There were lags of 130 to 150 ms between the hallux and little toe, whereas there were fewer lags among the MP joints (almost 0 ms) in both age groups.

For the cross-correlation coefficients between the COP_{ap} and each region (Figure 5(C)), the hallux showed the maximum coefficient in both age groups (both r = 0.452) as expected. The ANOVA regarding the COP_{ap} and the first ray (hallux and first MP) showed no significant interaction (age × region). The main effect of region was significant (F = 17.026, df = 1, $p < 0.001$, $\eta^2 = 0.20$); the hallux was larger than the first MP but not the effect of age. The ANOVA regarding the COP_{ap} and the fifth ray (little toe and fifth MP) showed no significant interaction or main effects, barring the main effect of age (F = 5.209, df = 1, p = 0.026, $\eta^2 = 0.071$) for the lags (Figure 5(D)).

Among the cross-correlation coefficients between the COP_{ml} and the first ray (Figure 5(E)), the ANOVA showed a significant interaction (age × region, F = 4.083, df = 1, p = 0.047, $\eta^2 = 0.057$). Both the main effects of age (F = 7.498, df = 1, p = 0.008, $\eta^2 = 0.099$) and region (F = 14.786, df = 1, $p < 0.001$, $\eta^2 = 0.179$) were significant. A paired t-test as a post-hoc test showed that the coefficient for the hallux was significantly lower than that for the first MP in both age groups (older: t = −3.021, df = 16, p = 0.008, r = 0.60, younger: t = −3.064, df = 18, p = 0.007, r = 0.59). A non-paired t-test showed that the coefficient for the older adults in only the hallux was significantly lower than that for the younger adults

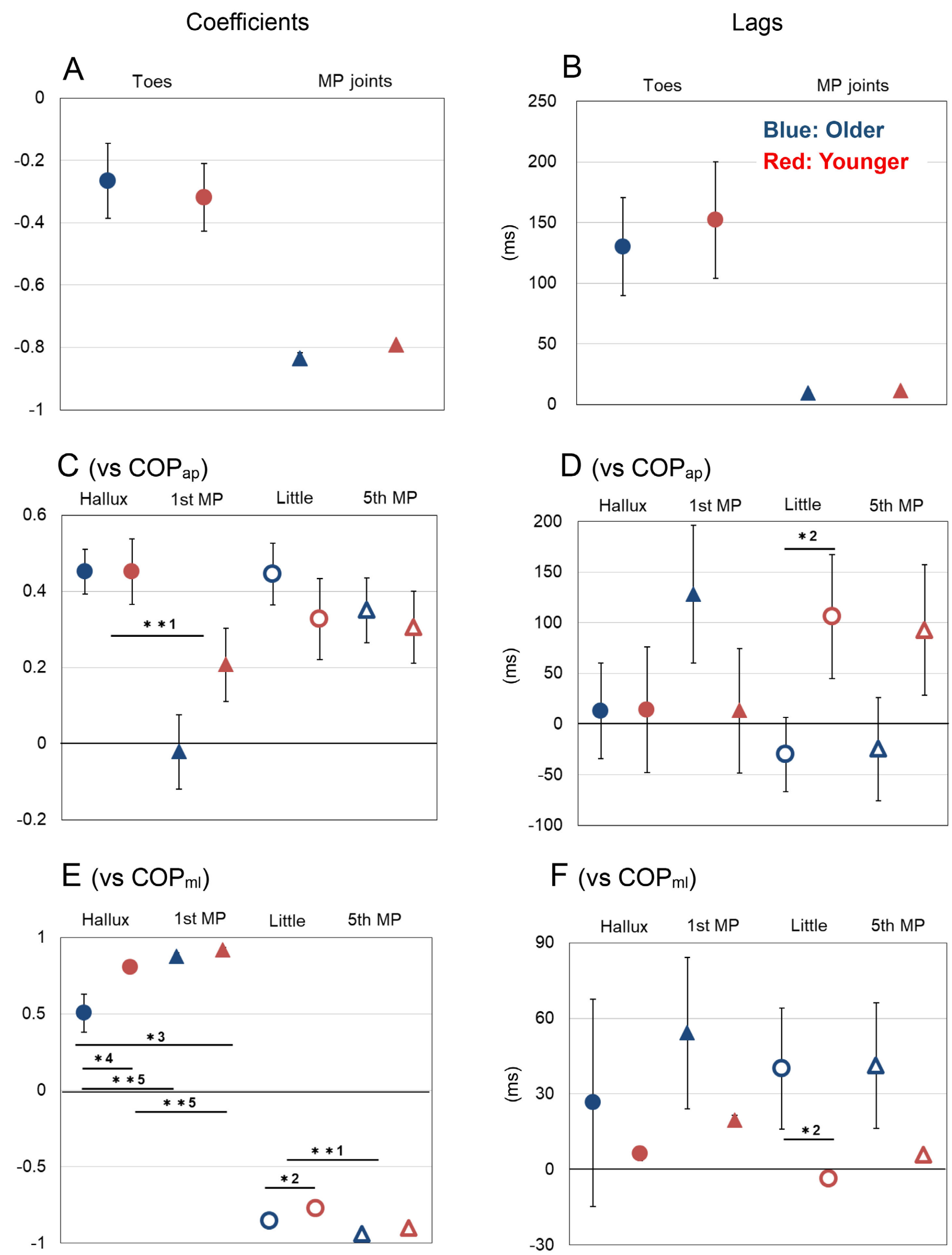

Figure 5. (A) coefficients of toes and MP joints; (B) lags of toes and MP joints; (C) coefficients between COP_{ap} and each region; (D) lags between COP_{ap} and each region; (E) coefficients between COP_{ml} and each region; (F) lags between COP_{ml} and each region. Blue and red symbols show the data of older and younger participants, respectively. Error bars: standard errors. **1: significant main effect of region, $p < 0.01$; *2/**2: significant main effect of age, $p < 0.05/0.01$; *3: significant interaction, $p < 0.05$; *4: significant non-pair t-test, $p < 0.05$; **5: significant paired t-test, $p < 0.01$.

($t = -2.325$, $df = 18.40$, $p = 0.032$, $r = 0.48$). Among the cross-correlation coefficients between the COP_{ml} and the fifth ray (Figure 5(E)), the ANOVA showed a significant main effect of age (F = 5.176, $df = 1$, $p = 0.026$, $\eta^2 = 0.071$) and region (F = 16.212, $df = 1$, $p < 0.001$, $\eta^2 = 0.193$). The older and little toe were higher than the younger and fifth MP, respectively. The lags regarding the COP_{ml} and the first ray showed no significant interactions or main effects, whereas the lags regarding the COP_{ml} and the fifth ray showed a significant main effect of age ($F = 5.785$, $df = 1$, $p = 0.019$, $\eta^2 = 0.078$) (**Figure 5(F)**).

The coefficients and lags regarding the COP_{ap} between the unstable and stable phases in older adults showed no significance. In contrast, the lags regarding the COP_{ml} and first MP joint showed a statistically significant difference ($t = -2.13$, $df = 18$, $p = 0.047$, $r = 0.45$) (**Table 3**). The lags between the timing of pressing the first MP in the stable and unstable phase were positive and negative, respectively.

Since all younger adults could maintain the OLS of 30 s, the Pearson's product moment correlation between the OLS duration and coupling variables was performed only for older adults. The OLS duration was significantly correlated with only the coefficient between the COP_{ml} and first MP ($r = 0.500$, $p = 0.041$). Each correlation coefficient is shown in **Table 4**.

Table 3. Coefficients and lags for each variable in the unstable and stable phases (n = 10).

			Coefficient			Lag (ms)		
			Unstable	Stable	*p* value	Unstable	Stable	*p* value
	Toes	Ave.	−0.088	−0.363	0.333	146.0	118.0	0.703
		S.E.	0.220	0.166		49.8	52.4	
	MPs	Ave.	−0.490	−0.835	0.147	104.0	12.0	0.316
		S.E.	0.225	0.028		44.0	4.4	
COP_{ap}	Hallux	Ave.	0.256	0.427	0.507	0	26.0	0.812
		S.E.	0.236	0.092		46.5	97.2	
	First MP	Ave.	0.388	0.020	0.191	−50.0	120.0	0.167
		S.E.	0.226	0.150		45.3	109.0	
	Little	Ave.	−0.048	0.352	0.114	22.0	−98.0	0.138
		S.E.	0.203	0.129		59.1	50.0	
	Fifth MP	Ave.	0.235	0.284	0.857	−70.0	−126.0	0.586
		S.E.	0.230	0.140		74.6	67.9	
COP_{ml}	Hallux	Ave.	0.048	0.629	0.075	−30.0	62.0	0.207
		S.E.	0.279	0.129		28.8	64.1	
	First MP	Ave.	0.484	0.855	0.112	−56.0	82.0	0.047*1
		S.E.	0.219	0.037		41.2	50.0	
	Little	Ave.	−0.703	−0.862	0.216	0	64.0	0.232
		S.E.	0.116	0.042		33.3	39.6	
	Fifth MP	Ave.	−0.909	−0.933	0.646	−4.0	64.0	0.176
		S.E.	0.034	0.040		24.0	41.8	

*The number of older adults participating in less than 30 s in was 10; *Lags for toes and MPs were calculated using absolute values; *Minus of lag indicated the phase delay relative to COP; *Ave: average, S.E.: standard error; *1: Significant difference between unstable and stable phases.

Table 4. Correlation between the OLS duration and each coupling variable in older adults (n = 17).

	COP_{ap}				COP_{ml}			
	Hallux	First MP	Little	Fifth MP	Hallux	First MP	Little	Fifth MP
Coefficient	−0.038	0.077	0.345	0.187	−0.054	0.500	0.060	−0.198
p value	0.886	0.769	0.175	0.472	0.836	0.041*	0.819	0.446

*: Significant correlation.

4. Discussion

This study aimed to clarify differences in the coordination among the toes and coupling between the COP and toes while maintaining the OLS in older adults as compared to younger adults.

4.1. Variables Regarding Center of Pressure

The RMS calculated in this study showed that the ML component was higher in the older participants (**Table 2**), which accords with findings from a previous study [23]. RMS represents an amplitude of the COP [27] [33]. Our findings indicate that the older participants swayed in the ML direction relatively more. This may have contributed to their shorter OLS duration. Furthermore, older adults who receive balance training show a smaller RMS of the COP during the OLS than their non-trained peers [25], which suggests that RMS is reversible. Future studies should investigate whether improving RMS during the OLS for older adults through training can improve other balance indexes and activities of daily living.

Our older participants showed faster MV in both the AP and ML directions than the younger participants (**Table 2**). This also accords with previous findings [24], including examinations of normal standing [27] [35]. It indicates that older and disabled individuals quickly move their COP to maintain equilibrium, possibly owing to muscle function impairment and the long latency response that is associated with aging [36]. As the long latency response involves slow muscle response to sensory inputs, impairment reflects an inability to move toes and feet slowly enough to change the COP. Furthermore, impaired slow response may also be associated with impairment of sensory reactions to low-frequency stimuli. Three sensory inputs (visual, vestibular, and somatic) are associated with maintaining balance [6]. Older adults have been found to have impaired somatosensory receptors, including pressoreceptors [6] [37]. Furthermore, there are receptors among these sensory inputs corresponding to the COP sway frequency [34]. Future studies should examine the relationships between COP movements and sensory inputs in older adults.

The ML_{mean} in the COP was not different between groups, but the AP_{mean} was more posterior in the older participants (**Table 2**), which indicated that older adults swayed in a more posterior position. When older adults stand on both feet, their COP is in a posterior position [3]. To our knowledge, no previous study has investigated COP/COM during the OLS, but we found the COP position in the OLS to be similar to that for standing on both legs [6]. This posterior COP position in older adults may be associated with impairment of toe functions [17]. As the gravity line travels anteriorly along the ankle joint as the COM moves anteriorly, COM can generate dorsi-flexion torque at the ankle joint. To restrict this torque, individuals increase the rigidity of their foot, activating their plantar flexor muscles. Thus, activation of the toe flexor muscles is necessary to make the foot rigid. As reaction forces on the foot from the floor (following plantar flexion of the ankle) can generate extension forces on the foot and toes, toe flexors must push on the floor to counteract these reaction forces. Impaired toe function weakens the ability to push on the floor, resulting in falls in an anterior direction. Since older adults attenuate toe muscle force [17], older adults may position COP posteriorly in order to not fall.

Since the variables regarding the COP in this study were similar to those in previous literature, we concluded that the variables in the present study were valid.

4.2. Coordination in Toes and MP Joints

The cross-correlation coefficients and the lag between the hallux and little toe did not show any significant difference between the groups. We originally hypothesized that the older adults would be less able to maintain the OLS because of impairment regarding switching between the hallux and little toe. However, our experiment did not show this to be true, with no difference detected between the groups regarding coordination between toes during the OLS. Even though muscle strength in the toes attenuates with aging [17], the coordination between toes in older adults was similar to that in younger adults. Although older adults showed significantly shorter OLS duration than younger adults, toe coordination (coordination between the hallux and little toe, including the first and fifth MPs) showed no difference between older and younger adults. Thus, the present study indicated that toe coordination was not associated with OLS duration.

4.3. Coupling between the COP and Toes or MP Joints

We hypothesized that the coupling between COP movement and the reaction of the foot regions differ with age. For the COP_{ml}, the coefficient between COP_{ml} and first ray (hallux and first MP) showed significant interaction, and the coefficient for the hallux showed a significant low value in older adults (**Figure 5(E)**). The low coefficients highlight the weak relationship between the COP_{ml} and hallux in older adults. Although a previous study reported that hallux was more involved with AP direction of COP movement than with ML direction, it compared the two directions using peak forces (*i.e.*, instantly) during fluctuation of COP [15]. This method could not clarify how hallux was involved in controlling COP over time. The present study investigated timeseries coupling between COP and hallux using a cross-correlation function. As a result, this study clarified that involvement of hallux with COP_{ml} over time was lower in older adults than in younger adults. Thus, coupling between hallux and COP_{ml} in older adults, who have a shorter OLS duration, was poorer than in youger adults. The cause of poor coupling between the hallux and COP_{ml} in older adults may be hallux impairment such as restricted ROM, muscle weakness, or low endurance. Further research is needed to clarify what type of impairment of the hallux (e.g., sensory factor [38]) generates poor coupling with COP movement.

The coefficient between the COP_{ml} and hallux did not significantly correlate with OLS duration. In contrast, the coefficient between the COP_{ml} and first MP was significantly correlated (**Table 4**). One reason why only the coefficient between COP_{ml} and first MP, and not that with hallux, was associated with OLS duration might be poor coupling between hallux and COP_{ml}. Younger adults in the present study showed a high coefficient of both hallux and first MP relative to COP_{ml} (**Figure 5(E)**). This finding indicated that, for younger adults, both hallux and first MP were involved with COP_{ml} movement. In contrast, older adults showed poor involvement of hallux with COP_{ml} movement, and the degree of contribution of first MP to control COP_{ml} would be larger because of this poor coupling. Thus, the coefficient between COP_{ml} and first MP, but not hallux, might be associated with OLS duration. Additionally, the lag of the first MP relative to the COP_{ml} in the unstable phase showed significant delay compared to that in the stable phase (**Table 3**). This finding indicates that, in the unstable phase, press of the first MP leads to a delay relative to COP medio-lateral movement. Older adults gradually cannot control COP fluctuation owing to delayed press of the first MP, for reasons such as fatigue, on the floor relative to the COP medio-lateral movement, especially in the medial direction, resulting in no maintenance of the OLS. Future research is needed to elucidate the interaction of hallux and first MP during OLS.

4.4. Limitations

Although the present study suggested that hallux impairments were associated with OLS capability in older adults, we could not clarify the functions in the hallux that affect maintenance of the OLS. It is possible that for older adults, muscle strength or endurance in the hallux regarding moving the COP is insufficient because they have attenuated toe muscle strength [17] and sensor functions in the plantar regions of the foot are impaired due to aging [39]. Since the plantar-pressure distribution system presented large hysteresis during a load/unload cycle, we were able to verify that there was no effect of hysteresis around the foot contact region in data recording using some weights. Therefore, the present data were valid. The sample size in the present study was small. However, since the effect sizes were large in almost all tests, this again validates the present study. Moreover, as this study used a cross-sectional design, the presented differences between older and younger adults could not reflect intra-individual changes with aging. However, the present findings in terms of the older adults' shorter OLS duration would suggest physical changes with aging.

5. Conclusion

This study found that the inability to maintain the OLS in older adults does not result from coordination impairments between the toes but is owing to the coupling of the first MP's vertical force relative to COP movement. This finding is novel, and future studies can elucidate the postural adjusting components (muscle strength; sensory, nervous, and central nervous systems; and endurance) and their effects on OLS maintenance. In terms of practical implications, developing the ability to maintain the OLS in older adults contributes to improving balance ability, resulting in fall prevention.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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