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Original Article

Comparison of timing and force control of foot tapping between elderly and young subjects

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Abstract. [Purpose] To examine the ability of young and elderly individuals to control the timing and force of periodic sequential foot tapping. [Subjects and Methods] Participants were 10 young (age, 22.1 ± 4.3 years) and 10 elderly individuals (74.8 ± 6.7 years) who were healthy and active. The foot tapping task consisted of practice (stimulus-synchronized tapping with visual feedback) and recall trials (self-paced tapping without visual feedback), periodically performed in this order, at 500-, 1,000-, and 2,000-ms target interstimulus-onset intervals, with a target force of 20% maximum voluntary contraction of the ankle plantar-flexor muscle. [Results] The coefficients of variation of force and intertap interval, used for quantifying the steadiness of the trials, were significantly greater in the elderly than in the young individuals. At the 500-ms interstimulus-onset interval, age-related effects were observed on the normalized mean absolute error of force, which was used to quantify the accuracy of the trials. The coefficients of variation of intertap interval for elderly individuals were significantly greater in the practice than in the recall trials at the 500- and 1,000-ms interstimulus-onset intervals. [Conclusion] The elderly individuals exhibited greater force and timing variability than the young individuals and showed impaired visuomotor processing during foot tapping sequences.

Key words: Foot tapping, Aging, Timing and force control

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INTRODUCTION

The timing and force of voluntary movements are important parameters in the coordination of movements. Several studies have used finger tapping tasks to clarify these two parameters[1–3)]. Inui et al.[4)] examined the interdependencies between timing and force production in a series of finger tapping tasks. The results showed that although variations in the intertap interval were controlled with considerable accuracy across conditions in finger tapping sequences, variations in force were not precisely controlled. These findings are supported by those of Keele et al.[5, 6)], who demonstrated that timing and force are controlled differently and that it is more difficult to control force than timing. Sternad et al.[7)], on the other hand, showed the interdependence between timing and force production in a wrist tapping task. Experimental systems that use finger tapping tasks often compare timing and force in practice trials, which are performed using visual feedback of timing and force exhibited in real time with a tempo, and in recall trials, without feedback or tempo. Sasaki et al.[8)] reported that in these tasks, finger tapping parameters are affected by age. At the 4-Hz frequency, all age groups had more-variable intertap intervals during the self-paced tapping than during the stimulus-synchronized tapping. The variability of the intertap intervals increased with age. The force variability of tapping at 4 Hz also increased with age. These findings point to an age-related increase in the timing

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*Corresponding author. Koji Takimoto (E-mail: ptrc.takimoto@tosareha.ac.jp) and force variability of finger tapping.

On the other hand, the timing and force of the lower limbs have been evaluated by using stepping tasks in which subjects were asked to walk in synchrony with a metronome[9, 10]. However, these studies did not find correlations between these two parameters, although several studies have investigated the characteristics of force control according to the isometric force exerted. Of particular interest are the reports[11, 12] that examined the effects of aging and visuomotor correction on force fluctuations in the elbow flexor and knee extensor muscles with and without visual feedback of the force. The results showed that 1) elbow flexor and knee extensor force fluctuations were greater when visual feedback of the force was provided and declined when feedback was removed; 2) at low muscle forces and high visual gain, the force fluctuations were greater for elderly adults only when visual feedback was provided; 3) at moderate and high muscle forces, when visual gain was lower, force fluctuations were greater for young adults than for elderly adults. Such age-related changes in force fluctuation were found in the ankle plantar flexor muscle as well[13]. According to these findings, the coefficient of variation (CV) of force is affected by the presence/absence of visual feedback, aging, and the degree of muscle force. Nonetheless, the mechanism underlying these characteristics remains unknown.

Typical periodic movements performed in daily life include chewing, scratching, and walking. Human walking requires particularly coordinated control of the timing and force of the lower limbs[14–17]. Moreover, in adult walking patterns (except when starting, stopping, or correcting), skillful movement is achieved through half-automated control[18]. Therefore, in terms of periodic movement, the lower limbs should be examined to ascertain the specific characteristics of timing and force control. The loss of lower limb timing and the failure of the mechanism controlling muscle contracture, such as in the gait disturbances typically found in Parkinson's disease[19–23], can have a huge impact on the daily lives of affected individuals.

The purpose of the present study was to examine fluctuations and accuracy of timing and muscle force by using a foot tapping task that involves periodic plantar flexion, with reference to earlier findings obtained from finger tapping and isometric muscle contraction tasks. This study discloses age-dependent variations in the control of timing and force of foot tapping and provides evidence of differences and similarities in characteristics between foot and finger tapping.

SUBJECTS AND METHODS

The subject sample comprised of 10 healthy young participants (mean age, 22.1 ± 4.3 years; range, 18–32 years; six male and four female participants) and 10 elderly participants (mean age, 74.8 ± 6.7 years; range, 65–83 years; three male and seven female participants) who were living independently in Japan. Only one lower limb was tested in the assays. To eliminate any influence caused by the difference in functioning between the left and right lower limbs, the dominant lower limb of each participant was identified by using the lower-limb dominance test proposed by Chapman et al[24]. In all the participants, the right lower limb was dominant. The elderly participants also underwent the Mini-Mental State Examination (MMSE)[25] for cognitive function assessment. The maximum MMSE score is 30 points, and a score of 24 points or higher is considered healthy[26]. In the present study, all the participants had a MMSE score of $\geq$24 points; therefore, task performance was not affected by their cognitive function. Any participants with a neurological disorder, a vision or hearing impairment, a significant bone or joint disease, or a pain-related disorder were excluded from the study. Prior to data collection, all the participants gave their written consent after being informed of the methods of the study and treatment of the measurement data. The experimental protocol was approved by the ethics committee of Tosa Rehabilitation College.

During the task, the participants were seated in a chair used for measurements, with their lower limbs positioned so that the hip and knee joints were at 90° and the ankle was in a neutral plantar flexion/dorsiflexion. A muscle force dynamometer (Frontier Medic Co., Ltd.) was placed directly under the right forefoot to allow for measurement of the muscle force exerted during ankle plantar flexion (Fig. 1). Data recorded from the muscle force dynamometer were subjected to analogue-to-digital conversion and entered in a PC (Inspiron 1150; Dell) at a sampling rate of 100 Hz. The distance from the participants' eyes to the PC monitor was approximately 1 m. The input data were saved as a KCT file, and the indexes were calculated from the data by using force analysis software (Emile Soft Co., Ltd.). A PC monitor (27-inch diagonal; LG Electronics Japan Co., Ltd.) was installed in front of the participants so that they were able to visually check the muscle force output level in real time. An electronic metronome (Seiko Co., Ltd.) served as an audiorhythm stimulus (frequency, 440 Hz) during the foot tapping task and was placed so that the participant could hear the tempo well.

Periodic movements such as tapping are of two types as follows: externally paced movements synchronous with an external stimulus (externally triggered movements) and actively performed self-paced periodic movements that require participants to complete independent periodic movements[5, 27]. In the present study, the practice and recall trials were organized with the experimental protocol based on these movements. In both trials, isometric plantar flexion (foot tapping) was performed periodically at three different interstimulus-onset intervals (ISIs) with a target muscular force output at 20% maximum voluntary contraction (MVC). In addition, prior to both tasks, the MVC of the ankle plantar flexor muscle was measured.

Prior to task performance, the participants were positioned for the task, and the isometric MVC of the ankle plantar flexor muscle was measured in the right lower limb. Maximal plantar force was measured by using a muscle force dynamometer placed directly below the right forefoot, and the participants were instructed not to lift the heel when exerting force. Plantar flexion was performed once at maximal force for 3 s, and the greatest force value (N) exerted during the 3 s was used as the MVC. The participants were allowed to practice once, after which MVC was measured. The target muscle force output that

Fig. 1. Experimental setup

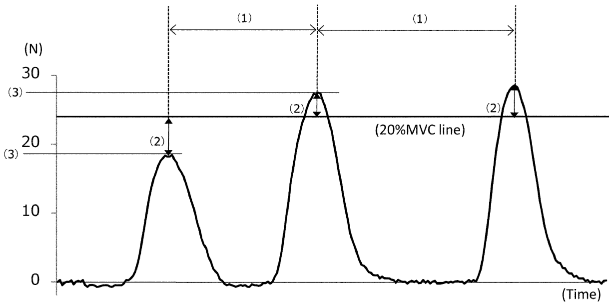

Fig. 2. A data sample of the peak-to-peak interval (1), muscular output error (2), and peak force (3)

was used in the subsequent tasks described below was calculated as 20% MVC.

In the practice trial, the participants performed foot tapping at three ISIs (500, 1,000, and 2,000 ms) in synchrony with an electronic metronome. At the same time, they checked the level of their muscle force by referring to a monitor placed in front of them, which displayed their current muscle force against a target muscle force output line equal to 20% MVC. The participants aimed to regulate their muscle force output so that the ankle plantar flexion waveform resulting from foot tapping matched the output line of the target muscle force. Foot tapping was performed in three sets, 60 times at each ISI. The data for 50 taps (the 11th–60th tap) during the third set were included in the analyses. The participants rested for 1 min between sets. The ISI values were determined based on those generally used in earlier studies[4, 7, 28)] and in the findings of Miyake et al.[29)] and Beck[30)]. Miyake et al. showed that the characteristics of finger tapping control (automatic and conscious control) changed respectively below and above 1,800 ms, and Beck showed that the walking pace of healthy adults (cadence) was 113 steps/min. The target muscle force was chosen; thus, the participants did not get tired even after repeated foot tapping.

In the recall trial, the tempo sound and monitor used in the practice trial were removed and the participants were asked to reproduce the foot tapping at the force and tempo that they showed in the practice trial. The recall trial was performed approximately 1 min after the third set of practice trials. Foot tapping was performed 60 times, and the data for 50 taps (the 11th–60th tap) were included in the analyses. In addition, to avoid any carryover effect from the order of ISIs given in each task, the order of ISIs was randomized for each participant.

The data recorded and saved from the muscle force dynamometer were processed by using force analysis software to determine the peak force (N) of the foot tapping used in the analyses and the peak-to-peak interval, which was used as the intertap interval (in milliseconds). Next, the peak muscle force difference (i.e., the difference between the peak and target muscle force [20% MVC]) and the intertap interval difference (i.e., the difference between the intertap interval and ISI) were calculated for each participant (Fig. 2). The mean constant error (CE, N) and absolute error (AE, N) of the peak force were normalized to each participant's MVC. Thereafter, the normalized mean CE and AE were calculated as study indexes of force control accuracy of foot tapping, whereas the CV (%) of peak force was calculated as an index of force steadiness. Furthermore, CE (ms) and AE (ms) of the intertap interval were calculated as indexes of the accuracy of timing of foot tapping, and the CV (%) of the intertap interval was calculated as an indicator of stability of the foot tapping interval. Values are expressed as means ± SD.

An unpaired t test was used to determine the presence or absence of a difference in the MVC of the ankle plantar flexor muscle measured in the MVC task between the young and elderly groups. For each of the three ISIs, a 2 (elderly vs. young group) ×2 (practice vs. recall trial) analysis of variance (ANOVA) was performed to examine the main effects and interactions of Group and Trial on the dependent variables. Significant F test results from the ANOVA were analyzed with the Bonferroni *post hoc* test. In all the tests, a p value of <0.05 was assumed to denote statistical significance.

RESULTS

The MVC of the ankle plantar flexor muscle that was measured in the MVC task was 147.9 ± 71.3 N (mean ± SD; 20% MVC, 29.6 ± 14.3 N) in the young group and 74.9 ± 38.1 N (20% MVC, 15.0 ± 7.6 N) in the elderly group. The unpaired *t* test revealed that the young group had significantly higher MVC values (p<0.05).

Table 1 displays the results on the three indexes of force (normalized CE, normalized AE, and CV) in the practice and recall trials for each of the three target ISIs. A 2 (Group) × 2 (Trial) repeated-measures ANOVA was performed for each ISI. A significant main effect on the normalized CE of force was found for Trial at the 2,000-ms ISI ($F_{[1,39]}=7.06$, $p<0.05$), with the recall trials (10.5 ± 15.0 N) showing greater normalized CE than the practice trials (2.4 ± 3.6 N). The *post hoc* test results showed that the elderly group had greater normalized CE in the recall trials than in the practice trials (p<0.01). No other significant effects on the normalized CE of force were found, nor any significant interactions of Group ×Trial.

Significant main effects on the normalized AE of force were found for Group at the 500-ms ISI ($F_{[1,39]}=6.89$, $p<0.05$) and

Table 1. Normalized constant error (CE), normalized absolute error (AE), and coefficient of variation (CV) of force periodically paced at an interstimulus-onset interval (ISI) of 500, 1,000, and 2,000 ms for the ankle plantar flexion of the young and elderly adults during practice and recall trials

		500-ms ISI		1000-ms ISI		2000-ms ISI	
		Practice	Recall	Practice	Recall	Practice	Recall
Normalized CE of force (N)	Young	0.5 ± 3.7	0.7 ± 2.8	1.4 ± 3.0	0.9 ± 2.2	1.5 ± 2.5	7.4 ± 10.0
	Elderly	−0.8 ± 4.7	−0.5 ± 6.3	0.8 ± 4.7	3.5 ± 8.7	3.3 ± 4.5	13.6 ± 18.7††
Normalized AE of force (N)	Young	4.2 ± 2.5	3.5 ± 1.6	3.4 ± 2.3	3.7 ± 1.6	3.7 ± 2.6	9.7 ± 8.7†
	Elderly	6.3 ± 3.2*	7.4 ± 4.2**	5.3 ± 3.1	7.6 ± 6.7	5.9 ± 3.5	16.7 ± 16.8††
CV of force (%)	Young	15.2 ± 4.5	12.7 ± 2.8	11.5 ± 2.6	15.9 ± 3.8	15.3 ± 5.7	14.4 ± 3.7
	Elderly	27.3 ± 13.9*	33.0 ± 25.9**	20.1 ± 12.1*	20.3 ± 13.4	16.0 ± 5.4	15.8 ± 5.3

Values are means ± SD. *p<0.05, **p<0.01 compared with young.
†p<0.05, ††p<0.01 compared with practice

Table 2. Constant error (CE), absolute error (AE), and coefficient of variation (CV) of intertap intervals periodically paced at an interstimulus-onset interval (ISI) of 500, 1,000, and 2,000 ms for the ankle plantar flexion of the young and elderly adults during practice and recall trials

		500-ms ISI		1000-ms ISI		2000-ms ISI	
		Practice	Recall	Practice	Recall	Practice	Recall
CE of intertap interval (ms)	Young	−2.2 ± 4.5	44.5 ± 69.5††	−0.7 ± 2.1	104.7 ± 129.4††	−0.9 ± 5.2	303.3 ± 392.2††
	Elderly	−16.0 ± 38.9	37.9 ± 52.3††	1.3 ± 64.0	20.3 ± 154.7	−10.2 ± 74.4	195.1 ± 359.6†
AE of intertap interval (ms)	Young	41.8 ± 14.5	69.6 ± 56.8	55.6 ± 23.8	139.7 ± 110.1	110.3 ± 30.3	383.7 ± 371.1
	Elderly	83.7 ± 52.0	83.0 ± 42.2	148.9 ± 98.3	138.5 ± 96.2	281.9 ± 185.2	347.7 ± 300.3
CV of intertap interval (%)	Young	8.5 ± 3.0	6.8 ± 2.1	5.7 ± 2.4	5.8 ± 2.0	5.6 ± 1.5	7.1 ± 3.0
	Elderly	16.8 ± 10.1**	11.6 ± 6.8*†	14.0 ± 8.8**	7.3 ± 1.6††	13.9 ± 8.5**	9.1 ± 4.3

Values are means ± SD. *p<0.05, **p<0.01 compared with young.
†p<0.05, ††p<0.01 compared with practice

for Trial at the 2,000-ms ISI ($F_{[1,39]}$=9.91, p<0.01), indicating that the elderly group (6.8 ± 3.7 N) had greater normalized AE than the young group (3.8 ± 2.1 N) at the 500-ms ISI. The recall trials (13.2 ± 13.5 N) showed greater normalized AE than the practice trials (4.8 ± 3.2 N) at the 2,000-ms ISI. The post hoc test results showed that the elderly group had greater normalized AE in both the practice (p<0.05) and recall trials (p<0.01) at the 500-ms ISI and that both the young and the elderly groups had greater normalized AE in the recall trials than in the practice trials at the 2,000-ms ISI (young, p<0.05; elderly, p<0.01). No other significant main effects on the normalized AE of force were found, nor any significant interactions.

Significant main effects on the CV of force were found for Group at the 500-ms ISI ($F_{[1,39]}$=7.30, p<0.05) and 1,000-ms ISI ($F_{[1,39]}$=5.51, p<0.05), indicating that the elderly group had greater CV than the young group at the 500- and 1,000-ms ISIs. The post hoc test showed that the elderly group had greater CV than the young group in both the practice (p<0.05) and recall trials (p<0.01) at the 500-ms ISI and in the practice (p<0.01) trials at the 1,000-ms ISI. That is, when foot tapping tasks were performed at the 500-ms ISI, the elderly group exerted less force accuracy and steadiness than the young group, and both the young and the elderly group produced force with less accuracy during the self-paced tapping than during the stimulus-synchronized tapping at the 2,000-ms ISI.

Table 2 displays the results on the three indexes of intertap interval (CE, AE, and CV) in the practice and recall trials for each of the three target ISIs. As is the case with force, a 2 (Group) × 2 (Trial) repeated-measures ANOVA was performed for each ISI. Significant main effects on the CE of intertap interval were found for Trial at the 500-ms ($F_{[1,39]}$=12.43, p<0.01), 1,000-ms ($F_{[1,39]}$=4.83, p<0.05), and 2,000-ms ($F_{[1,39]}$=8.80, p<0.01) ISIs, indicating that the recall trials had greater CE than the practice trials at the 500-, 1,000-, and 2,000-ms ISIs. The *post hoc* test showed that both the young (p<0.01) and elderly (p<0.01) groups had greater CE in the recall trials than in the practice trials at the 500- and 2,000-ms ISIs, and that the young group had greater CE in the recall trials than in the practice trials at the 1,000-ms ISI (p<0.01). No significant interaction was found on the CE of intertap interval at any of the three ISIs.

No significant main effect on the AE of intertap interval for Group or Trial were found at any of the three ISIs, nor significant interaction of Group × Trial. Significant main effects on the CV of intertap interval were found for Group ($F_{[1,39]}$=7.00, p<0.05) and Trial ($F_{[1,39]}$=6.10, p<0.05) at the 500-ms ISI and for Group ($F_{[1,39]}$=11.06, p<0.01) at the 2,000-ms ISI. Moreover, a significant interaction of Group × Trial ($F_{[1,39]}$=5.51, p<0.05) was found at the 1,000-ms ISI. The post hoc test showed that the elderly group had greater CV than the young group in the practice (p<0.01) and recall trials (p<0.05) at the 500-ms

ISI, the elderly group had greater CV than the young group in the practice trials at the 1,000-ms ISI ($p<0.01$) and 2,000-ms ISI ($p<0.01$), and the elderly group had greater CV in the practice trials than in the recall trials at the 500-ms ISI ($p<0.05$) and 1,000-ms ISI ($p<0.01$). That is, the elderly group exhibited a less steady intertap interval than the young group, but the unsteadiness in the elderly group was reduced when visual feedback was removed.

DISCUSSION

Regarding the control of timing and force of periodic foot tapping sequences, the notable results of this study were that the CVs of force and intertap interval, which were used to quantify the steadiness of the trials, were significantly greater in the elderly group than in the young group. Age effects on the normalized mean AE of force were observed at the 500-ms ISI, which was used to quantify the accuracy of the trials. The CVs of the intertap interval for the elderly group were significantly greater in the practice (stimulus-synchronized tapping with visual feedback) than in the recall (self-paced tapping without visual feedback) trials at the 500- and 1,000-ms ISIs, which was in marked contrast to the finding that the elderly group had more variable intertap intervals in the recall than in the practice trials of finger tapping sequences at the 4-Hz frequency8). Therefore, the greater variability in the practice trials for the elderly group may be regarded as a peculiar characteristic of foot tapping and suggests age-related decrements in visuomotor processing during the foot tapping sequences. In fact, the age-related decrements in visuomotor processing have been shown to contribute to age-related differences in force control31, 32). The cerebellum33, 34) may be associated with motor timing during the stimulus-synchronized movement, whereas the basal ganglia appear to be involved in motor timing during the self-paced movement35, 36). Therefore, abnormal motor signs due to dysfunction of the cerebellum in the elderly group are speculated to have partly contributed to the greater variability in the stimulus-synchronized tapping.

An important result of the present study in terms of force control is that the elderly group showed an increase in the CV of peak force along with an increase in tempo. Sasaki et al.8) used finger tapping to demonstrate that the CV of peak force is greater in individuals aged ≥70 years than in individuals in their 20s and 60s. Christou and Carton37) reported that the CV of peak force for knee flexion decreases with increases in muscle force in both young and elderly individuals, but the CV is greater in elderly individuals. Likewise, Sosnoff et al.31) reported that the use of the same percentage of MVC results in weaker individuals producing a greater CV of force. Therefore, age-related differences in force may partly contribute to the age-related changes in force variability. Consequently, the age-related changes in force variability may be more fundamentally due to the association between strength and force variability. On the other hand, Sternad et al.7) examined the two-way effect of timing and force during finger tapping, and demonstrated that the CV of force stabilizes as tapping speed increases. Considering these results altogether, the present finding that the variation in the CV of force during foot tapping increased with increasing tempo in the elderly group may be regarded as a peculiar characteristic of foot tapping. Ikegami et al.38) conducted an experiment that involved moving a handle periodically (2.5 Hz) and reported that erroneous information received by the brain in the first movement cycle had a negative effect on movement correction in subsequent cycles. By contrast, in the fourth and fifth cycles, learning outcomes improved when visual information was given only once. Their results suggested that continuously received information is not processed well by the brain. Therefore, during the relatively quick foot tapping at the ISI of 500 ms in the present study, the elderly individuals were unable to control force well and the force exerted fluctuated.

Another important result of the present study in terms of force control is that the normalized CE and AE of force were significantly greater in the recall trials than in the practice trials during foot tapping only at the ISI of 2,000 ms. The decreased accuracy at the ISI of 2,000 ms was probably due to increased attentional and working memory-related cognitive demands as the ISI increased39). Miyake et al.29) conducted a study in which a dual synchronous finger tapping task using periodic sound stimuli ranging from 300 to 4,800 ms was performed in parallel with silent reading. When the ISI was <1,800 ms, the decrease in attentional resources due to the performance of dual tasks did not affect the results of the synchronous tapping task. Nonetheless, at the ISI of ≥1,800 ms, the synchronous tapping task was strongly affected by the decrease in attentional resources because of the execution of dual tasks. In support of this notion, a previous report indicated that elderly individuals perform more poorly than young individuals when they were requested to successfully execute more than one action at a time while paying attention to two or more channels of information40). Taken together, these facts indicate that the decreased accuracy of the recall trials at the ISI of 2,000 ms may be partly attributed to the decrease in the divided attention capacity of the elderly group.

An important result of the present study in terms of timing control is that the CV of the intertap interval was greater in the elderly group than in the young group. Nagasaki et al.41) conducted a study with a synchronous finger tapping task with a 4-Hz tempo and detected a Parkinson's disease-like anticipatory tapping response, the occurrence of which increased with age. Similarly, by using a finger tapping task, Sternad et al.7), Elazary et al.42), and Sasaki et al.8) all showed that the variation in the intertap interval increases with age. This phenomenon may be attributed to the neurological effect of aging. In brain imaging studies, Thaut and his colleagues described the neural networks involved in finger tapping in synchrony with metronome-like pulse beat sequences. Activated regions include primary sensorimotor and cingulate areas, bilateral opercular premotor areas, bilateral SII, ventral prefrontal cortex, anterior insula, putamen, thalamus, and ventral regions and anterior hemispheres of the cerebellum43). With aging, histochemical degeneration of the nigrostriatal pathway develops in the basal ganglia, resulting in dysfunction of the basal ganglia-cortical loop[44]. Accordingly, this phenomenon may have influenced the increase in the intertap interval CV in the elderly group.

Another important result of the present study in terms of timing control is that significant main effects on the CE of intertap interval were found only for Trial and indicated that the recall trials have greater CE than the practice trials. Sasaki et al.[8] showed that task had no significant effect on the means of the intertap intervals during finger tapping sequences, although a significant main effect of age for the 250-ms task was found. In the present study, the greater CE of the intertap intervals in the recall trials than in the practice trials may be regarded as a peculiar characteristic of foot tapping. The CE of the intertap intervals was much greater at an ISI of 2,000 ms. Higher brain functions such as attention and working memory has been shown to be possibly involved in perception of ISI length[45]. Furthermore, in their experiment in which patients with damage to the cerebellum and prefrontal area performed a time discrimination task with two conditions, namely at 400 ms and at 4 s, Mangels et al.[39] revealed the importance of working memory in time perception. Therefore, it is possible that the longer the ISI, the greater is the involvement of the prefrontal area. Consequently, it is highly difficult to control time perception through attention and working memory. Similarly, the results of the present study indicate that the error in the intertap interval increased as ISI increased.

This study has several limitations. First, the tasks in this study were performed with a target muscle force output at 20% MVC. Nevertheless, to conduct the study in accordance with the earlier findings of constant-force trials, various muscle force levels should also be studied in lower limb tapping tasks. Moreover, in the present study, the force could be controlled through visual feedback. Although metronome beeps were used as a guide to control timing, feedback on whether the timing was synchronized with the beeps could not be provided. Therefore, the possibility that the orientation of attention during the practice trials tended to shift toward force control could not be excluded. In addition, the foot tapping movement is made via the periodic isometric muscular contraction of one ankle joint. Considering the future possible application of the present findings to walking, foot tapping using both lower limbs should be examined by using experiments similar to those used by Inui et al.[46] and Matsumoto et al.[47] in the study of bilateral finger tapping.

In the present study, the dominant effects of age on the variability of the force and timing of unimanual foot tapping sequences were observed. Further studies are needed to elucidate the characteristics of the periodic movement of the lower limbs and thereby develop new strategies for gait rehabilitation and injury prevention.

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