

The Influence of Aging on Balance Function in Terms of the Foot Electromyographic Reaction Time

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Abstract. [Purpose] This study examined the influence of aging on balance function through the reaction time of the ankle joint muscles. [Methods] Forty-nine subjects were classified into 3 age groups: aged 20 to 30 (group Y, 19 subjects); aged 60 to 74 (YO, 12); and over 75 (OO, 18). Functional reach (FR), single-leg standing with eyes closed (SLS), and plantar flexor strength, were measured. For the electromyogram responses, reaction time (RT), premotor time (PMT), motor time (MT) and anticipatory postural adjustments (APAs) were evaluated. [Results] Significant differences in FR and SLS were observed between Y and YO, and OO. In the standing position, significant differences in PMT were observed between Y and OO, and in MT among all age groups. For the APAs, significant differences were observed between Y and OO, and in the strength between Y and YO, and OO. Balance items appeared to correlate with the reaction time in the standing position. [Conclusion] The results of this study verify that the balance function declines with age. We demonstrated that a delay in central processing and slower muscle contractions are key factors in the age-related decline of the balance function.

Key words: Electromyographic reaction time, Balance function, Aging

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INTRODUCTION

Humans became able to perform a wide range of activities and lead creative lives after beginning to walk on two legs. A smaller base of support for two-legged walking, however, involves difficulty in maintaining balance and an increased risk of falling. In the elderly, particularly, falls tend to cause fractures and injuries, occasionally resulting in physical impairment or a bedridden condition. The relationship between aging and balance function is a key issue in an aging society, such as Japan, which needs to be continuously examined following existing findings¹⁾.

The importance of maintaining balance is increased in a standing position, which is an important risk factor for falls. Shumway-Cook¹⁸⁾ reported three functional strategies for postural control: the “ankle strategy” performed by the ankle joint and its muscles; the “hip strategy” to restore equilibrium; and the “stepping strategy”, in which the length of a step is used to make a new base of support. When standing on a hard base of support, the ankle strategy is primarily used, and its role as an interface between the floor and body is crucial. Based on this idea, this study focused on the relationship between aging and the ankle strategy.

In addition, to understand this strategy in terms of the muscle reaction of the ankle joint, the time elements of the electromyogram responses were analyzed. In electromyography, the reaction time (RT) is defined as the period of time from the onset of the triggering stimulus to the onset of movement; the interval between the onset of the stimulus

and the appearance of waves is defined as the premotor time (PMT), and that between PMT and the onset of movement as the motor time (MT)¹⁴⁾. According to these definitions, PMT represents the transmission components of postural adjustment, including central processing, while MT indicates the process of force application, involving kinetic factors. In some cases of complicated postural control, the muscle reaction and movement for postural adjustment take place anteriorly to drive movement toward an objective. Such a reaction is called an anticipatory postural adjustment (APA), and is considered an important factor complementary to postural control^{2, 6, 8)}.

Up to the present, a large number of basic studies examining electromyographic reaction times have been conducted^{3, 16, 26)}, and APAs have been studied in connection with postural control^{11, 27, 28)}; however, few studies have examined age-related changes. Although the relationship between the balance function and reaction time has been examined in some studies, including a study of 105 subjects by Tokumori and colleagues²²⁾, most of these studies examined the systemic reaction time, which is the period of time from the onset of the triggering stimulus to the onset of physical movement. Very few studies have focused on the muscles of the ankle joint and examined their relationships with balance function in terms of the age-sorted components of the electromyographic reaction time. Therefore, this study aimed to confirm the age-related decline in balance function and examine the influence of aging on postural control in the standing position in terms of the foot reaction time and its

Table 1. Subject attributes

	Total	Group Y	Group YO	Group OO
Subjects, number	49 (25)	19 (10)	12 (5)	18 (10)
Age, years		21.9 ± 2.4	68.1 ± 3.5	80.4 ± 3.2
Height, cm		166.0 ± 7.1	159.3 ± 8.5	153.5 ± 8.5
Weight, kg		57.5 ± 9.0	56.6 ± 12.7	57.6 ± 8.0

Note: () female, values are mean ± SD

components. Determining the characteristics of the reaction time of aging foot muscles may be important for enhancing understanding of postural control and the influence of aging on it in order to improve the balance function.

SUBJECTS AND METHODS

Subjects

A total of 49 subjects were classified into 3 age groups: “young” aged 20 to 30 (group Y, 19 subjects); “young-old” aged 60 to 74 (YO, 12); and “old-old” over 75 (OO, 18) (Table 1). All subjects were physically independent without a history of significant neurological and/or orthopedic disease or impairment, including deformation. Their auditory abilities were sufficient for daily activities. None of them had mental dysfunction, such as dementia. Each subject was provided with a written and oral explanation of the study objectives and details, and those whose consent was obtained were studied.

Methods

Four measurements were conducted in each group: 1) functional reach (FR) and 2) single-leg standing (SLS) time with eyes closed to evaluate standing balance; and measurements of plantar flexion reaction times in 3) the supine and 4) standing positions. In addition, 5) the plantar flexor strength was also measured to evaluate muscle strength. Measurements 1) to 5) were conducted in this order in quiet individual rooms.

For the electromyographic system, a PH700 AD Conversion Board and DAQCard-6036E (DKH) were used to measure reaction times along with a multi-purpose data analysis program IFS-4G (DKH) installed on a personal computer (PC; NEC). Dry, fixed-type electrodes (SX230; Biometrics) were employed. Myographic signals were sampled at a frequency of 1,000 Hz, using a high-pass filter with a cutoff frequency of 10 Hz; the values below this were excluded. A delay of 0.110 s was observed in sound production, which was deducted from the measured values. Electrodes were placed at intervals of 2 cm on the following muscles: the tibialis anterior (1/3 above the horizontal line between the inferior border of the patella and lateral malleolus and the gastrocnemius lateral head (1/3 above the horizontal line between the head of the fibula and calcaneal tubercle)²⁵). The non-dominant leg, which is used as a pivot leg²³, was measured.

The functional reach test, developed by Duncan⁷, was used to evaluate static balance. The subjects were asked to stand upright parallel to a wall with their feet shoulder-width

apart and the arm adjacent to the wall raised at 90 degrees, with the elbow joint extended. They were asked to reach forward at the height of the raised arm, and their maximal horizontal-forward movement of the upper limb was recorded. During this movement, the subjects were not allowed to compensate knee flexion or trunk rotation. The mean values of 3 measurements were used in the analysis.

Single-leg standing time with eyes closed was also used to evaluate balance. It is based on the method put forward by the Laboratory of Physical Fitness Standards²³. Subjects were asked to stand in their bare feet and hands on the waist, and to subsequently close their eyes. Measurement started when they raised a single leg based on their own timing. The criteria for ending measurement were: touching the floor with the raised leg; opening the eyes during the test; changing the pivot foot; losing balance; and a lapse of 2 minutes. The mean values of 3 measurements were used in the analysis.

To measure the plantar flexion reaction time in the supine position, we used an original device comprising a mobile panel connected to foot movements and a switch to cut off the voltage supplied by an AA battery (1.5 V). The device was installed on the foot of each subject in the supine position. The switch-controlled voltage was used as an external trigger and input into the AD conversion board for synchronization with muscle signals. Subjects were prompted with an electric sound stimulus (approximately 7 kHz, 30 dB) as a starting signal from the PC through the left headphone. The initiation of electromyographic measurement and the onset of electric sound were controlled by keyboard commands. The starting signal was produced randomly around three seconds after the researcher issued the “get set” command to the subjects who had their eyes closed. The subjects were instructed to perform plantar flexion as soon as they heard the signal. The mean values of 3 measurements following several rehearsals were employed (Fig. 1-A).

The electromyographic reactions were categorized as follows: from the signal generated by the PC to the onset of actual movement (reaction time: RT); from the signal to the muscle reaction (premotor time: PMT); and the time difference between RT and PMT (motor time: MT). The starting point of each reaction was defined as the time the amplitude was 1.5 times higher than the mean before contraction¹¹.

For the measurement of plantar flexion reaction time in the standing position, a copper plate was installed on the plantar surface of the heel, and another on the floor, to form a point of contact between them. The circuit comprised a switch to cut off the voltage supplied by an AA battery (1.5 V) when the heel was raised. The other conditions were sim-

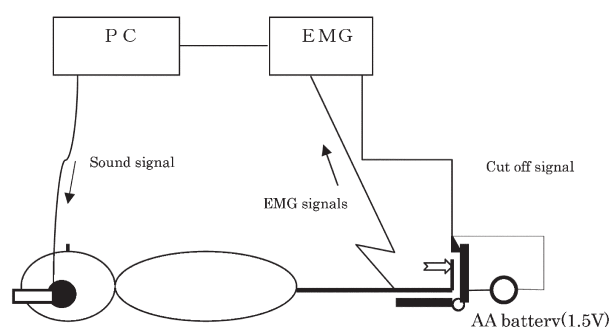
ilar to those used in the supine position. The subjects were instructed to stand on two legs and raise both heels simultaneously as fast as possible when they heard the starting signal approximately 3 seconds after the “get set” command. When standing, the subjects were asked to keep their feet shoulder-width apart, and imagine their weights were centralized at the mid-point between their feet. Both arms were hung down naturally by the side of the body. Measurements were conducted with the subjects’ eyes open and looking horizontally forward. The mean values of 3 measurements following several rehearsals were used in the analysis (Fig. 1-B). In the standing position, the dorsiflexor activity (tibialis anterior) preceding the plantar flexor reaction was considered as an APA.

For the measurement of plantar flexor strength, the subjects were instructed to sit with their legs extended straight out on an originally designed measurement board with 2 back supports. A non-flexible nylon band attached to the back supports was placed around the foot plantar surface by the sides of the legs, so that the leg to be measured (the same as that measured for the reaction time) was stably supported, and a manual dynamometer (μ -Tas MF01: Anima Corporation) was installed on the plantar surface. The subjects were instructed to freely perform maximal plantar flexion for 5 seconds, and its strength was recorded. The mean values of 3 measurements were employed (Fig. 1-C).

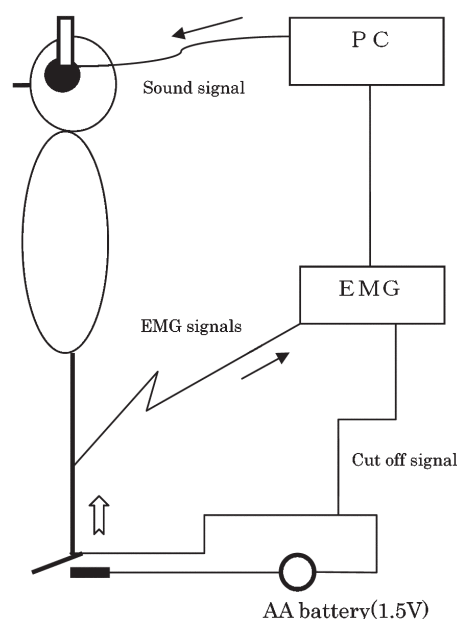
The data was tested for normal distribution and equal variance. For comparisons among the 3 groups, one-way analysis of variance and multiple comparisons (Fisher’s LSD) were performed in cases of equal variance, and the Kruskal-Wallis and multiple comparison tests (Steel-Dwass method) were performed in other cases. For evaluation of correlation, we used Spearman’s rank correlation coefficient. The significant level in each test was 5%.

RESULTS

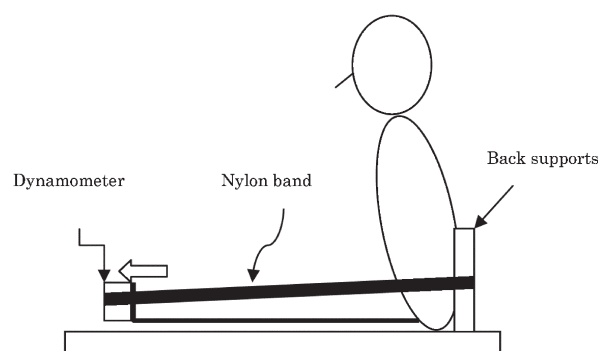
The measured values of each item were compared among groups Y, YO, and OO (Table 2). Functional reach, FR decreased with age, and significant differences in the reach distance were found between groups Y and YO, and Y and OO. Single-leg standing time with eyes closed also decreased with age, similar to FR and significant differences in the SLS time were found for between groups Y and YO, and Y and OO. In the plantar flexion reaction time in the supine position, an age-related delay was found for all items (RT, PMT, and MT); however, no between-group significant differences were found for any of the items. In the plantar flexion reaction time in the standing position, an age-related delay was found for all items (RT, PMT, MT, and APAs) and the difference in RT between groups Y and OO was significant; the difference in PMT between Y and OO was also significant. For MT, significant differences were found between Y and YO, Y and OO, and YO and OO, and a significant difference in APAs was found between Y and OO. The plantar flexor strength values measured with the manual dynamometer were divided by the weight and multiplied by 100 to compare ratios (to weight). The results demonstrate an age-related decline, with significant differences between



A: The system used to measure the plantar flexion reaction time in the supine position



B: The system used to measure the plantar flexion reaction time in the standing position



C: Measurement of plantar flexor strength

Fig. 1 Measurement environment

groups Y and YO, and Y and OO.

To examine the relationship between the balance indicators (FR and SLS) and plantar flexion reaction times in the supine and standing positions, correlation coefficients were calculated. The results show no correlation between FR and any of the reaction time items (PMT, MT, and RT) in the su-

Table 2. Mean values in each age group

					Significance		
		Group Y	Group YO	Group OO	Y-YO	Y-OO	YO-OO
Functional reach (FR), cm		35.4 ± 5.4	28.1 ± 4.5	23.9 ± 7.9	**	**	ns
Single leg standing (SLS), s		48.3 ± 41.9	5.9 ± 10.4	1.8 ± 1.2	**	**	ns
Muscul strength, %		103 ± 21	64 ± 33	42 ± 11	**	**	ns
Supine position, s	RT	0.242 ± 0.045	0.253 ± 0.073	0.278 ± 0.080	ns	ns	ns
	PMT	0.200 ± 0.045	0.207 ± 0.083	0.222 ± 0.073	ns	ns	ns
	MT	0.042 ± 0.014	0.046 ± 0.027	0.056 ± 0.018	ns	ns	ns
Standing position, s	RT	0.415 ± 0.088	0.473 ± 0.113	0.591 ± 0.175	ns	**	ns
	PMT	0.304 ± 0.077	0.333 ± 0.100	0.389 ± 0.124	ns	*	ns
	MT	0.112 ± 0.021	0.140 ± 0.038	0.202 ± 0.061	ns	**	*
	APA	0.147 ± 0.045	0.156 ± 0.038	0.204 ± 0.107	*	ns	ns

Note: values are mean ± SD, RT: Reaction time, PMT: Pre motor time, MT: Motor time, APA: Anticipatory postural adjustments

*: $p < 0.05$ **: $p < 0.01$. ns: not significant

Table 3. Correlation with the balance indicators

	RT-Sp	PMT-Sp	MT-Sp	RT-St	PMT-St	MT-St	APA	FR, SLS
FR				-0.504**	-0.405**	-0.553**		
SLS				-0.562**	-0.391**	-0.612**	-0.378**	0.605**

FR: Functional reach; SLS: Single leg standing; RT-Sp: Reaction time, supine; PMT-Sp: Pre-motor time, supine; MT-Sp: Motor time, supine; RT-St: Reaction time, standing; PMT-St: Pre-motor time, standing; MT-St: Motor time, standing; APA: Anticipatory postural adjustments. Note: omitted coefficient of correlation ± 0.3 or less. **: $p < 0.01$

pine position. In the standing position, in contrast, significant correlations with all items, except for APAs, were found. Similarly, for SLS, significant correlations were found with all the reaction time items, and also with APAs (Table 3).

DISCUSSION

In this study, FR and SLS were focused on to examine the relationship between the balance function and aging. The FR test, developed by Duncan and colleagues⁷⁾, is considered to be highly reliable, and standard measures and inter-rater reliability have been verified. Giorgetti and colleagues⁹⁾ reported that FR may be a useful balance indicator in both healthy and impaired elderly subjects. SLS was adopted in this study to equalize the measurement conditions, shutting out visual information¹⁷⁾. It has been incorporated into the Japanese standard of physical fitness by the Laboratory of Physical Fitness Standards²³⁾, and is considered to be highly reliable as a normal value of the balance function. Both measures demonstrated significant differences between the young (Y) and elderly groups (YO and OO), confirming the influence of aging on balance function.

Each component of the electromyographic reaction time was interpreted as follows. Based on the findings of Cordo and Nashner⁶⁾, the motion-controlling central nervous system commands a driving movement toward an objective when stimulated by sensory information; however, in the postural control program, a postural adjustment takes place in anticipation of it. This explains why, in the standing position, although raising the heels as a movement toward an

objective was driven by auditory stimulus, contracting the tibialis anterior muscle to incline the trunk forward as an APA, commanded by the postural control program, preceded it. As a result, the center of gravity remained within the base of support, maintaining the posture even while standing on tiptoe. Such an APA may be considered as a feed-forward reaction, as it was observed in the tibialis anterior activity, while PMT of the gastrocnemius to raise the heels may have represented a driving movement toward an objective. These results were compared with those in the supine position, which is not involved in the postural control program, to analyze the relationship of the reaction time. In PMT in the supine position, although an age-related delay was observed, it was not significant. On the other hand, in the standing position, significant differences in PMT of the gastrocnemius were observed between groups Y and OO. This may be explained by a greater influence of aging due to the postural control process, which is incorporated into central processing as an APA, consequently complicating the overall control processes. As APAs were observed in all groups, including the elderly, the postural control program itself appears to function independently of age. At the same time, however, an age-related delay in the manifestation of APAs and significant differences between groups Y and OO were observed. These results demonstrate that driving movements toward postural control as feed-forward reactions or APAs are also affected by aging. Although the transmission components include the peripheral synaptic transmission process, a number of studies have reported that this process is not affected by aging¹²⁾; therefore, the delays in PMT and

APAs may reflect a delay in central processing. Tokitou and colleagues²¹⁾ measured and compared the P300 components of event-related potentials in 6 young-elderly males aged 65 to 68 and 8 healthy young males aged 22 to 26 in order to examine the influence of aging on the central nervous system and processing. They reported that a delayed latency was observed in the elderly, and this finding is consistent with the results of this study.

The determinants of MT include the mechanism of motor unit manifestation, physical conditions, such as muscle load and elasticity, as well as the muscle contraction velocity. In this study, an age-related delay in MT in the supine position was observed, although it was not significant. On the other hand, in the standing position, the delay was more marked, showing significant differences between groups YO and OO, as well as between Y and OO. The muscle contraction velocity is easily focused on during plantar flexion in the supine position, as it is practically independent of the physical load. The condition during MT in the standing position differs in that it requires raising the heels while bearing weight, and, the greater load on the plantar flexor muscles must have increased the influence of muscle strength, in addition to the muscle contraction velocity. The results of this study indicate that the muscle contraction velocity decreases along with a decline in the maximum permissible load due to aging. Among several types of muscle, the activity of type II fibers, fast muscles, becomes dominant when a fast contraction is required^{13, 20)}, such as that required for the measurement in this study. Age-related muscle atrophy involving a decrease in the diameter of type II muscle fibers (atrophy) has been reported to markedly develop in the elderly aged over 85^{4, 24)}. Based on these findings, it may be appropriate to explain the delay in MT in this study as a decreased muscle contraction velocity as a result of age-related atrophy chiefly of type II muscle fibers and a decline in muscle strength. Regarding the relationship between plantar flexor strength and aging, the age-related decline in muscle strength and significant differences between groups Y and YO, and Y and OO demonstrate that lower-limb strength and muscle contraction velocity also play important roles in balance and the foot reaction time.

In the analysis of the correlation coefficients between the balance items and electromyographic reaction time, FR was shown to have a negative correlation with the reaction time items in the standing position; but no correlations were found in the supine position or with APAs. A similar tendency was observed for SLS, which additionally showed a negative correlation with APAs. These results demonstrate that the foot reaction time can be used as an indicator of balance function in functional postures, such as the standing position, confirming the importance of the ankle strategy in postural control. Similarly, the result that APAs solely correlate with SLS may be explained as follows. While FR is a movement which slowly moves the trunk forward while maintaining balance, SLS is a less stable state supported by a single leg without visual compensation. To maintain the posture in this unstable condition, an APA is performed¹⁵⁾.

The results of this study confirm that balance function declines with age, and is associated with the foot electro-

myographic reaction time in the standing position. They also reveal that both a delay in central processing of postural control and a lower muscle contraction velocity due to a decline in muscle strength are factors associated with the age-related changes in balance function in terms of the foot reaction time. From this viewpoint, determining the characteristics of the electromyographic reaction time of the foot and examining their time-dependent variation may be important for the understanding of qualitative changes in balance function. Furthermore, as reported in previous studies^{5, 10, 19)}, the fact that the influence of aging on balance function involves a decreased muscle contraction velocity due to a decline in muscle strength suggests the possibility of maintaining and improving the balance function of the elderly by strengthening the muscles of the ankle joint. In line with these results, further studies will be conducted to examine the effect of muscle-strengthening approaches on balance function, and to evaluate the changes in central processing under different conditions, such as complicated postural control and various trigger stimuli.

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