J. Phys. Ther. Sci. 36: 492–497, 2024

The Journal of Physical Therapy Science

SPTS

Original Article

Percentage of decline in individual proprioceptors in older adults

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Abstract. [Purpose] Although standing balance and functions of each proprioceptor decline with age in older adults, data regarding the types and percentages of proprioceptors susceptible to decline are unavailable. In this study, we investigated the rate of decline in each proprioceptor area in older adults and also the effect of aging on the association between postural balance and proprioception. [Participants and Methods] This study performed between November 2012 and July 2022 included both young and older adults. Vibration stimuli were applied to the gastrocnemius and lumbar multifidus muscles at 30–250 Hz to assess the effects of the easily attenuated proprioceptors. The independent t-test showed a decline in proprioception in older adults. A χ^2 test was performed to determine proprioceptors that were susceptible to attenuation in older adults. [Results] The results revealed that many older adults had reduced muscle spindles (low and high frequencies) in their lower legs and trunk (low frequency). [Conclusion] Proprioceptive ability is lower in older adults than in younger individuals. Therefore, activation programs to treat the reduced intrinsic receptive responsiveness may be required for rehabilitation of older adults.

Key words: Older adult, Postural balance, Proprioception

(This article was submitted Feb. 21, 2024, and was accepted Jun. 2, 2024)

INTRODUCTION

Physical function declines due to aging, making it difficult to maintain a stable standing posture. This leads to falls and reduces daily activity, resulting in bedriddenness and disuse syndrome[1)]. Maintaining a stable standing posture requires the ability to maintain balance by keeping the center of gravity within the plantar surface of the foot[2)]. Three types of sensory information are required to sustain a standing posture: visual, somatosensory, and vestibular. Maintaining the balance of a healthy person in standing posture depends on 20% visual information, 70% somatosensory information, and 10% vestibulo sensory information[3)]. However, when the visual information is limited, the degree of dependence on other senses varies depending on the situation, and the sensory information is re-organized[4–6)]. Somatic sensations are classified into skin sensations and proprioception provided by proprioceptors, each of which has a frequency band for response to mechanical vibrations. Pacinian corpuscles transmit skin sensations from the soles of the feet, providing the necessary feedback to maintain balance[7)]. However, their response frequency varies between individuals and ranges from 140 to 250 Hz[8, 9)]. Proprioception

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*Corresponding author. Kazunori Yamazaki (E-mail: k-ymzk@daido-it.ac.jp) is the internal sense of body position essential for regulating balance and generating and maintaining accurate movement patterns10). Muscle spindles, which provide proprioception for the muscles of the lower legs and trunk, play an important role in maintaining postural stability11). Furthermore, their response frequency varies between individuals and ranges from 30 to 100 Hz9, 12). Stimulation to mechanical vibration is widely used to investigate the relationship between proprioception and balance maintenance9, 13–16).

Previously, we developed a device that measures stimulation to mechanical vibration at any frequency. In a study using this device, Kawai et al. defined a new index for assessing proprioception and reported cutoff values for estimating functional decline and the rate of proprioception decline in young healthy participants17). In addition, Ito et al. reported that older people show more dependence on proprioception of the lower legs than younger people due to aging18, 19), implying that proprioception and postural balance decline with age in older adults. However, the proportion of each proprioceptor that tends to deteriorate in older adults remains unclear and needs further assessment before its application in treatment programs. Therefore, this novel study assessed the rate of decline in each region of proprioception in older adults and investigated the effects of aging on the relationship between postural balance and proprioception.

PARTICIPANTS AND METHODS

In this observational study, we conducted a survey of older adults based on the Kawai et al. method17) published by our research group and compared the results with previously published data on young adults17). The older adults who participated in this observational study were recruited between November 2012 and July 2022. Ethical approval was granted by the National Center for Geriatrics and Gerontology Ethics Committee (IRB# 1405). Written informed consent was obtained from all participants before their participation in the study. The study was conducted in accordance with the principles of the Declaration of Helsinki. The study included a total of 280 older adults who were either hospitalized or attended the National Center for Geriatrics and Gerontology and did not require assistance in maintaining a standing position. Additionally, participants with vestibular dysfunction, vertebral compression fracture, spinal tumor, spinal cord infection, paralysis, ataxia, neurological disorders, balance disorders, a history of spinal surgery, leg pain, or lower back pain were excluded.

For the assessment of proprioception (Fig. 1), each participant stood barefoot with their feet together on a balance board or stabilometer. Their eyes were closed using an eye mask, and they were instructed to remain still and relax with their arms hanging loosely on their sides. The longitudinal displacement of the center of pressure (COP) was measured when a mechanical vibration stimulus with a response frequency of 30–250 Hz of each proprioceptor was applied. COP displacement was recorded using a balance board (Wii, Nintendo Co., Ltd., Kyoto, Japan) or stabilometer (T.K.K. 5810; Takei Scientific Instruments Co., Ltd., Niigata, Japan). The COP data were calculated using MATLAB (MathWorks Inc., Natick, MA, USA). The input sine wave signal for mechanical vibration stimulation was generated using a PC. The input signal lasted 75 s, with a pre-section consisting of 15 s with no vibration, followed by a continuous sine wave from 27–272 Hz (frequency up mode) or 272–27 Hz (frequency down mode) for 60 s change. The input signal was an output of the voice-coil vibrator via an amplifier and acted as a continuous mechanical vibration stimulus with an amplitude of 0.8 mm. Stimulus of mechanical vibration was applied to the gastrocnemius and soleus muscles (GS) and lumbar multifidus (LM) muscles, which are important for postural control, alternately with 60 s of rest in the sitting position12).

For the analysis of proprioception, we used the modified root mean square (modified RMS) and cutoff values calculated from the anteroposterior displacement of the COP17). A modified RMS was used to assess the ability to maintain balance without a vibratory stimulus. The greater the sway of each evaluation section (ES) in the vibration interval compared with the pre-interval, the greater the value. Equations (1)–(4) (reproduced from equations (3)–(6) in Kawai et al.)17) indicate that the larger the value, the better the function of the intrinsic receptors that provide intrinsic sensation.

$$RMS_{*}^{1} = \frac{\sqrt{\frac{1}{N}\sum_{n=n_1}^{n_2}\left\{Y_{Vib(*)}(n)-\bar{Y}_{pre(*)}\right\}^{2}}}{RMS_{*}^{pre}} \quad (1)$$

$$RMS_{*}^{2} = \frac{\sqrt{\frac{1}{N}\sum_{n=n_3}^{n_4}\left\{Y_{Vib(*)}(n)-\bar{Y}_{pre(*)}\right\}^{2}}}{RMS_{*}^{pre}} \quad (2)$$

$$RMS_{*}^{3} = \frac{\sqrt{\frac{1}{N}\sum_{n=n_5}^{n_6}\left\{Y_{Vib(*)}(n)-\bar{Y}_{pre(*)}\right\}^{2}}}{RMS_{*}^{pre}} \quad (3)$$

$$RMS_{*}^{pre} = \sqrt{\frac{1}{N}\sum_{n=1}^{301}\left\{Y_{pre(*)}(n)-\bar{Y}_{pre(*)}\right\}^{2}} \quad (4)$$

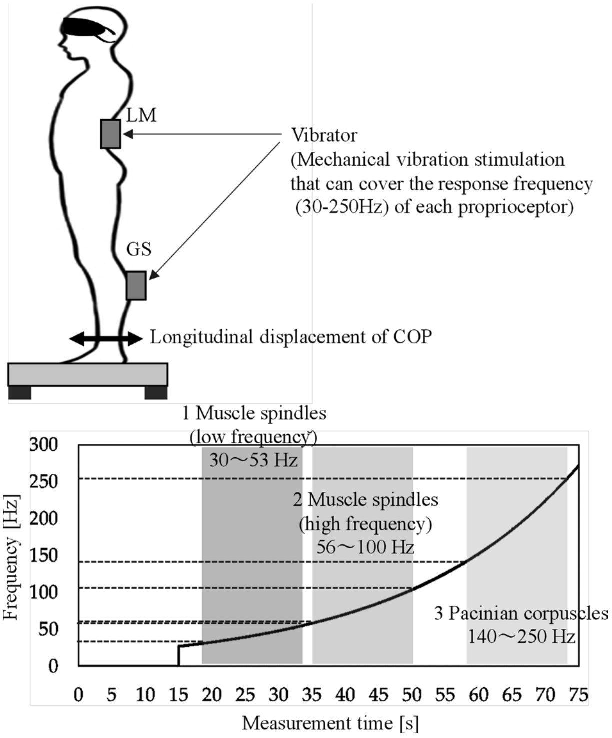

Fig. 1. Schematic diagram of the clinical trial and the three analysis intervals based on the proprioceptor response frequency (Frequency ascend mode).

Vibratory stimuli varying in a wide range of frequencies from 30 to 250 Hz and corresponding to the response frequencies of approximately all proprioceptors (muscle spindles (low frequency), muscle spindles (high frequency), and pachyonychia bodies) are used to diagnose proprioceptor function in older adults.

Vibration stimulation was applied to the bilateral lumbar multifidus and gastrocnemius muscles of both legs with continuous mechanical vibration from low to high frequency (or high to low frequency). The displacement of the center of pressure during vibration of the trunk and lower legs was automatically recorded using a stabilometer to assess proprioceptor function. Longitudinal displacements of the center of pressure (COP) were analyzed as waveforms using a stabilometer. LM: lumbar multifidus; GS: gastrocnemius and soleus muscles.

In this Equation, 'n' denotes the number of data series. "Y_{Vib}" represents the CoP in the anteroposterior direction during the vibration section, while "$\overline{Y}_{pre}$" signifies the average CoP in the anteroposterior direction during the pre-section. The subscript "*" is used to differentiate the location of the stimulator, denoted as either GS or LM. Additionally, the subscript number distinguishes between different experimental sessions (ES). Furthermore, "N" in the Equation symbolizes the total number of sampled data points for each ES, which is fixed at 300. This is because all experimental sessions were analyzed within a 15-s timeframe, given a sampling frequency of 20 Hz[17]. Three ES were defined based on the response frequency of the proprioceptors: 1) muscle spindles (low frequency) 30–53 Hz, 2) muscle spindles (high frequency) 56–100 Hz, and 3) pacinian corpuscles 140–250 Hz. Comparisons between younger and older adults in the three assessment intervals in Equations (1)–(3) were confirmed to have a probability of significance of less than 5% using t-tests. Furthermore, the cutoff value representing the decline in the intrinsic receptive function was determined using Equation (5) (reproduced from Equation (7) in Kawai et al.)[17].

$$Cutoff^{i}_{GS,LM} = \overline{RMS^{i}_{GS,LM}} - \sigma_{RMS^{i}_{GS,LM}} \quad (5)$$

As people who sway less in response to vibration have reduced proprioceptive function[20], a reduction in proprioceptive function was estimated when the sway of the center of gravity in the front-back direction was below the cutoff value upon application of vibration. For comparison between young adults[17] and older adult participants, the proportion of persons whose sway to the vibration stimulus site and proprioceptor response frequency bands were below the cutoff value was calculated. However, owing to overlapping areas of decreased proprioception, the percentage decrease in each index within each group surpasses 100%. Furthermore, they were confirmed to have a probability of significance <5% using the χ^2 test.

Based on the aforementioned, this study first compared the young and older adults based on the modified RMS shown in equations (1)–(3) to confirm the age-related decline in proprioception (Table 1 is equivalent to Kawai et al.'s Table 2[17]). Subsequently, based on the cutoff value for young, healthy individuals shown in Equation (5)[17], the rate of decline in proprioception in the lower limbs and trunk in the young and older adults is evaluated (Table 3). As noted earlier, there is overlap in the areas where proprioception is degraded, hence the total may exceed 100%. Finally, based on the cutoff value for young, healthy individuals shown in Equation (5)17), we evaluated the areas susceptible to aging-related deterioration and the rate of decline in proprioception (Table 1, equivalent to Kawai et al.'s Table 217)). Similarly, due to overlapping areas of proprioception decline, the total may exceed 100%.

RESULTS

Table 4 shows the demographics of the study participants, including the 81 young adults in Kawai et al.'s17) paper as a baseline and the 280 older adults in the present study. Table 1 presents the functioning of proprioceptors among the study groups. The results showed significantly smaller values for older adults and significantly larger values for young adults at all three evaluation intervals for the trunk and lower legs.

Tables 2 and 3 indicate the comparison of reduced proprioceptive sensation in the study groups. Table 3 shows the percentages of study participants with no decline in proprioception, decreased proprioception in any of the lower legs, decreased proprioception in the trunk, and decreased proprioception in both the lower legs and trunk. Table 2 reveals a reduction in the following proprioceptors: the muscle spindles of the lower legs (low frequency), muscle spindles of the lower legs (high frequency), Pacinian corpuscles of the lower legs, muscle spindles of the trunk (low frequency), muscle spindles of the trunk (high frequency), and Pacinian corpuscles of the trunk. These results confirm that older adults have a significantly

Table 1. Percentage of below the cutoff and no decline in lower legs and trunk frequency ranges in young and older adults

	Young adults (n=81)	Older adults (n=280)	p-value
RMS^1_{GS}	2.09 ± 1.08	1.47 ± 0.82	***
RMS^2_{GS}	2.82 ± 1.80	1.58 ± 0.88	***
RMS^3_{GS}	2.50 ± 1.81	1.46 ± 0.67	***
RMS^1_{LM}	1.99 ± 1.14	1.34 ± 0.59	***
RMS^2_{LM}	2.22 ± 1.37	1.39 ± 0.62	***
RMS^3_{LM}	2.06 ± 1.41	1.39 ± 0.58	***

Data are presented as the mean ± standard deviation.
All p-values were determined using the independent t-test *p<0.05; **p<0.01; ***p<0.001.
RMS: root mean square; GS: gastrocnemius and soleus muscles; LM: lumbar multifidus. 1 Muscle spindles (lower frequency): 30–53 Hz; 2 Muscle spindles (higher frequency): 56–100 Hz; 3 Pacinian corpuscles, 140–250 Hz.

Table 2. Percentage distribution of proprioception based on site and frequency range in the study groups.

	Young adults (n=81)	Older adults (n=280)	p-value
Percent below $cutoff^1_{GS}$	9.9%	25.0%	**
Percent below $cutoff^2_{GS}$	8.6%	20.0%	*
Percent below $cutoff^3_{GS}$	2.5%	3.2%	
Percent below $cutoff^1_{LM}$	4.9%	15.0%	*
Percent below $cutoff^2_{LM}$	4.9%	12.5%	
Percent below $cutoff^3_{LM}$	1.2%	2.1%	

All p-values were generated using the χ^2 test *p<0.05; **p<0.01; ***p<0.001.
GS: gastrocnemius and soleus; LM: lumbar multifidus. [1]Muscle spindles (lower frequency), 30–53 Hz; [2]Muscle spindles (higher frequency), 56–100 Hz; [3]Pacinian corpuscles, 140–250 Hz.
The percentage [%] is the number of people who fell below each cutoff value divided by the total number of people (n).

Table 3. Percentage distribution of lower legs and trunk proprioception in the study groups

	Young adults (n=81)	Older adults (n=280)	p-value
No decline in proprioception	76.5%	44.3%	***
Declined proprioception in the lower legs	14.8%	38.9%	***
Declined proprioception in the trunk	11.1%	25.4%	**
Declined proprioception in both trunk and lower legs	2.5%	8.6%	

The percentage [%] is the number of people who fell below each cutoff value divided by the total number of people (n).
All p-values were generated using the χ^2 test *p<0.05; **p<0.01; ***p<0.001.

Table 4. Demographic characteristics and functional outcomes of young and older adults

	Young adults (n=81)	Older adults (n=280)
Age, years	22.49 ± 4.13	75.56 ± 5.23
Height, cm	166.42 ± 8.91	155.40 ± 8.60
Weight, kg	57.77 ± 9.39	59.58 ± 11.7
Body mass index, kg/m^2	20.76 ± 2.18	24.55 ± 3.72
Gender, Female/Male	33/48	136/144

Data are presented as the mean ± standard deviation.

higher percentage of no decline in proprioception. In older adults, proprioceptors are reduced due to aging, evidenced by the percentage of those with any loss of proprioception in the lower legs, the trunk, muscle spindles in the lower legs (both low and high frequencies), and lower muscle spindles in the trunk (high frequency).

DISCUSSION

This study compared the proprioception function among healthy young and older adults and revealed that all the proprioceptors in the older group had reduced function than young adults. A larger percentage of older adults also had reduced proprioceptive function. Furthermore, it revealed the reduced function of the lower leg muscle spindles (low frequency), lower leg muscle spindles (high frequency), and trunk muscle spindles (low frequency). Therefore, this study is the first to demonstrate the rate of decline in each eigensense in older adults.

Previous studies indicate that proprioception can be evaluated by measuring the longitudinal displacement of the COP when a stimulus of mechanical vibration is applied. Mechanical vibration stimulates the primary afferent artery of the muscle spindle, which provides proprioception. Furthermore, the better the proprioceptive function, the greater the fluctuation in postural balance as a biological response13). Our group demonstrated stimulation of each proprioceptor by mechanical vibration covering a response frequency of 30–250 Hz and confirmed that biological reactions occur based on the response frequency of each proprioceptor. In this study, many young people showed a large postural sway in response to stimulus to vibrations, whereas many older adults showed a small postural sway. This finding indicates that older adults experience a decline in proprioception due to aging. Our study showed a reduction in proprioceptors in older adults, which is attributed to aging. More participants had lower than the cutoff values for the lower leg muscle spindles (low frequency), lower leg muscle spindles (high frequency), and trunk muscle spindles (low frequency); this may be attributed to a decline in the function of muscle spindles due to the age-related loss of muscle mass. Muscle spindles exist within muscles, sense muscle elongation, and are important for maintaining posture. However, as muscle mass decreases, their function also decreases21). Therefore, we can infer that the decrease in muscle mass associated with aging is related to the function of muscle spindles. The rate of loss of muscle mass ranges between 1% and 2% per year over the age of 50 years, resulting in a loss of 25% for those under 70 years and 40% for those over 80 years of age22, 23).

In a study by Kawai et al., the modified RMS and cutoff values were calculated from the anteroposterior displacement of the COP17). The results confirm that older adults have lower proprioception than younger people. Therefore, we can conclude that the indicators used in previous studies are correct.

This study has several limitations. First, we only examined the decline in intrinsic receptivity in older and young adults. Evaluating the decline in intrinsic receptivity after middle age may provide insights into the process of age-related decline. Second, this study did not assess the impact of the decline in intrinsic receptivity. Evaluating this could provide more information and suggestions on the possible effects of reduced patient intrinsic receptivity. Furthermore, as older adults tend to have reduced muscle spindles, an intrinsic receptor activation program should be created and used to optimize the treatment of reduced intrinsic receptive responsiveness. Additionally, assessing the tendency toward decreased intrinsic receptive sensations may be important for the rehabilitation of older adults.

In conclusion, we examined the decline in proprioceptive sensation in younger and older adults. The percentage of each eigensensory decline by region was used to investigate the effect of aging on the relationship between postural balance and eigensensory perception. We confirmed that many older adults had decreased muscle spindles (low- and high-frequency bands), especially in the lower legs and trunk (low-frequency band), which may be related to the decrease in muscle mass associated with aging.

Funding

No benefits in any form have been or will be received from a commercial party for this study.

Conflict of interest

Authors have no conflict of interest to declare.

ACKNOWLEDGMENT

The authors thank all the staff and patients who contributed to this study.

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