International Journal of New Technology and Research (IJNTR)
ISSN:2454-4116, Volume-4, Issue-7, July 2018 Pages 15-20

Development of a Novel Testing and Training Device of Proprioceptive Sensory for Standing Balance Ability in the Elderly and Disabled Individuals

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***Abstract*—<Background> Traumatic injuries and fractures resulting from falls by elderly individuals have become a major issue for the government bodies responsible for health, medical care, and social welfare because they markedly reduce the individuals' ability to engage in activities of daily living. Major causes of such falls by elderly individuals are decreased balance ability and impairment associated with aging. Proprioceptive information obtained by movement of the lower extremity muscles and joints are important for maintaining balance. However, there have been very few studies concerned with further quantifying lower extremity proprioceptive sense, which for elderly individuals is important for maintaining standing balance. The objectives of this study were to develop the first device to quantitatively evaluate changes in the proprioceptive threshold (motion sense and joint position sense) that is associated with changes in the angle of the ankle during standing and, based on this evaluation, establish methods of evaluating and training joint sense that are needed to improve balance ability by using a new device.**

<Methods> The subjects were five elderly individuals (mean 71.4 years) and seven young individuals (mean 20.6 years) who were not proficient at sports. A new device was used to evaluate the motion sense and the joint position sense during plantar flexion, dorsiflexion, inversion, and eversion of the ankle with the individual in the standing position. The device was shown to be capable of measuring ankle proprioceptive sense during standing to 1 degree of accuracy. The subject stood with their dominant foot on the motor-driven foot plate of the device. Next, the motor-driven plate was inclined at a specified angular velocity, and the subject was instructed to stop the plate by pressing a button near their hand when they felt that the inclination angle matched that of the non-dominant leg. Four movement directions were used for the ankle: dorsiflexion, plantar flexion, eversion, and inversion. The two dorsiflexion angles used were 5 and 10 degrees; the three plantar flexion angles were 5, 10, and 15 degrees; the two eversion angles were 5 and 10 degrees; and the three inversion angles were 5, 10, and 15 degrees. The two angular velocities used were 1 and 2 degrees/sec. For the analysis, the inclination angle of the non-dominant foot was used as the set angle, and the angle at which the subject stopped the plate was used as the stop angle. The error (| set angle - stop angle |) was the test parameter. The minimum error value obtained in the two trials was recorded. In the analysis, the two groups were compared with respect to this error value.

<Results> The results of this study showed that the decrease in ankle proprioceptive sense in elderly individuals varied with changes in dynamic joint movement during standing. Also, the results showed sensory differences between elderly and young individuals.

<Conclusion> The device developed for this study can measure ankle proprioceptive sense, which is an important element of standing balance ability. In the future, we hope to improve measurement accuracy by combining a variety of joint movement velocities and sensory evaluation methods and establish balance training techniques that use this device.

***Index Terms*— standing balance, elderly, new proprioceptive sensory evaluation, rehabilitation device.**

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I. Introduction

Traumatic injuries and fractures resulting from falls by elderly individuals have become a major issue for the government bodies responsible for health, medical care, and social welfare because they markedly reduce the individuals' ability to engage in activities of daily living.

Figure. 1 A new device for measuring proprioceptive sense of the ankle joint

The 2012 vital statistics released by the Ministry of Health, Labour and Welfare (MHLW) showed that elderly individuals aged 65 years or older accounted for 6,607 of the 7,761 deaths caused by falls that year. Eighty percent of these falls were caused by slipping or tripping. Survey of Living Conditions for 2013, fall-related fractures ranked fourth among the main reasons why elderly individuals aged 65 years or older required long-term care, and more than 190,000 femoral fractures resulting from falls occurred that year. Major causes of such falls by elderly individuals are decreased balance ability and impairment associated with aging. Tactile sensory information obtained through contact of the toes and plantar surfaces with the floor or ground (base of support) and proprioceptive information (motion sense and joint position sense) obtained by movement of the lower extremity muscles and joints are important for maintaining balance. Decreased balance ability in elderly individuals is not only the result of a decline in motor function involving factors such as muscle strength. A decline in the sensory function of the toes, plantar surfaces, and ankles is also thought to play a role. Using a novel device for measuring tactile-pressure sensation of the toes, Tanaka et al. found such sensation to be significantly reduced in elderly individuals as compared with young individuals, even though those elderly individuals could carry out activities of daily living without difficulty. They concluded that sensory input from the toes is important for standing balance [1 - 2]. To evaluate dynamic balance ability, which is important for standing balance and walking, the group also fabricated a device with an oscillating floor for external disturbance stimulation and analyzed this ability in elderly individuals [3 - 4]. However, there have been very few studies concerned with further quantifying lower extremity proprioceptive sense, which for elderly individuals is important for maintaining standing balance.

Standing balance ability is one of the most important therapeutic goals for patients in many different circumstances; for example, patients who have just undergone lower limb surgery, those with joint sprain, and those at a high risk of falls. Postural control is composed of integration of visual, somesthetic and vestibular information [5 - 6]. In situations where the stable stance is perturbed, afferent sensory input is processed by the central nervous system which reacts to select, trigger, and control the appropriate postural response [7]. For quiet standing, ankle proprioception is thought to be an essential component for establishing the internal organization required for performing a motor task [8].

As proprioception is a complex process that relies on the integration of sensory input from many receptors, it is susceptible to the deleterious effects of early stages of disease. Therefore, critical and objective assessment of proprioception is not only important for early detection of proprioceptive loss, but may also be helpful in quantifying this loss with aging. Rehabilitation programs have been suggested for maintaining proprioception in affected patients, but further research is needed to establish the benefits of exercise for proprioception. Minimal changes in proprioception that may signify an important diagnosis often escape detection partly because of the lack of reliable and valid methods for quantifying joint position and movement sense.

Joint position sense (JPS) and kinesthesia have been measured as indices for evaluating impairment of joint proprioceptive sense [9 – 16]. In many of these studies, ankle JPS testing has been used as an index of impaired joint proprioceptive sense that indicates impaired input of afferent information. Glencross et al. performed measurements in individuals with functional ankle instability (FAI) and healthy subjects using a passive evaluation method in which the examiner passively moved the ankle of the subject into plantar flexion. They found that angle misrecognition was significantly greater in the FAI group than in the healthy

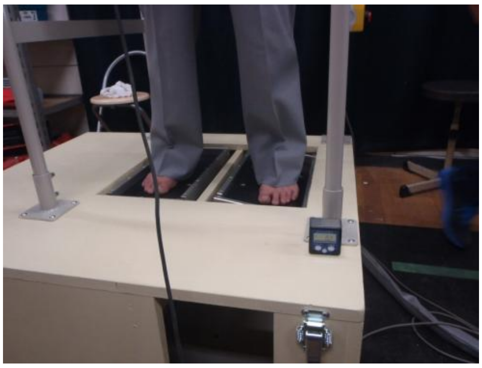

Figure. 2 Standing position on the motion-driven foot plate during movements of the ankle joints.

group [9]. On the other hand, there are also reports of no differences between the FAI and healthy groups [11]. Thus, views on ankle JPS in individuals with FAI vary depending on the investigator, and this may be attributable to the use of different measurement conditions and methods.

Either active or passive evaluation methods are used for measurements in JPS testing. With an active evaluation method, the test is performed while the subject actively moves the joint by muscle contraction. A passive evaluation method is one in which the examiner passively moves the joint. However, views vary regarding the differences between active and passive evaluation methods [13 – 14]. In particular, it is not known how these differences are affected by ankle proprioceptive sense during standing that is associated with changes in the angle of the ankle, which is important for standing balance.

The objectives of this study were to develop the first device to quantitatively evaluate changes in the proprioceptive threshold (motion sense and joint position sense) that is associated with changes in the angle of the ankle during standing and, based on this evaluation, establish methods of evaluating and training joint sense that are needed to improve balance ability by using a new device.

II. METHODS

A. Subjects

The subjects were five elderly individuals (aged 71.4 ± 4.5 years) and seven young individuals (aged 20.6 ± 0.5 years) who were not proficient at sports. All subjects were right-handed, and none had a condition that interfered with their daily life. The dominant leg, defined as being the leg the subject used to kick a ball, was the right leg for all of the subjects (reference). Written consent to participate in the study was obtained from all of the subjects. This study received the approval of the Ethics Committee of the University of Tokyo (15-248).

B. *Ankle proprioceptive sense (motion sense and joint position sense) testing device*

An ankle proprioceptive sense testing device that measured the motion sense and the joint position sense of the ankle was developed (Fig. 1 and 2). The device was used to evaluate the motion sense and the joint position sense during

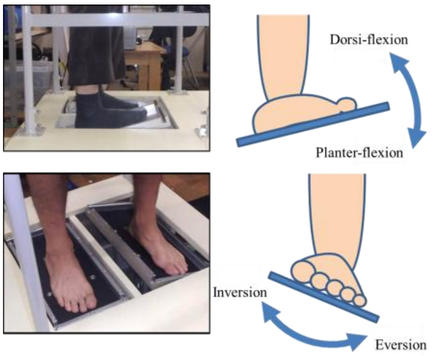

Figure. 3. Two axis movements of the ankle on the motion-driven foot plate device; dorsi-plantar flexion and inversion-eversion

Table 1. The specification of new device

items	product specification
Range of the angle of foot-plate	-45°～45°
Angle velocity of a foot-plate	0.2～22.5°/s
Resolution of the velocity of foot-plate	0.1°/s
Rated load load	100kgf

plantar flexion, dorsiflexion, inversion, and eversion of the ankle with the individual in the standing position (Fig. 3). The device was equipped with two foot-plates. One was a fixed plate whose angle was set manually. The other was a motor-driven plate whose angle could be controlled arbitrarily using a servomotor. Both plates could be placed in plantar flexion or dorsiflexion and inversion or eversion and fixed in that position. The platform was equipped with handrails to the left and right of the subject to prevent falls. A feature of the device was that it allowed ankle proprioceptive sense to be tested along two axes, inversion/eversion and plantar flexion/dorsiflexion. With one leg placed on the platform set to a fixed angle (fixed platform) and the other on the platform whose angle could be adjusted with a motor (motor-driven platform), the subject pressed a button to stop the platform when he or she felt that the two platforms were at the same angle. The motion sense and the joint position sense of the ankle were then evaluated by measuring the difference between the angles of the two foot-plates. The specifications of the device are shown in Table 1.

C. Measurement and analysis of proprioceptive sense using the device

The device was used to measure ankle proprioceptive sense in the same five elderly and seven young individuals. The procedure involved fixing the manual foot plate to a preset inclination angle and putting the motor-driven foot plate in the horizontal position. The subject then stood with their dominant foot on the motor-driven foot plate of the device (Fig. 2). Next, the motor-driven plate was inclined at a specified angular velocity, and the subject was instructed to stop the plate by pressing a button near their hand when they felt that the inclination angle matched that of the non-dominant leg. Four movement directions were used for the ankle: dorsiflexion, plantar flexion, eversion (valgus), and inversion (varus) (Fig. 3). The two dorsiflexion angles used were 5 and 10 degrees; the three plantar flexion angles were 5, 10, and 15 degrees; the two eversion angles were 5 and 10 degrees; and the three inversion angles were 5, 10, and 15 degrees. The two angular velocities used were 1 and 2 degrees/sec. Two trials of the test were performed under each condition. To eliminate the effects of vision and hearing, the subjects were required to wear an eye mask and headphones (Fig. 4). To prevent falls, the platform was equipped with handrails, and two staff members stood nearby during testing. Information on the subject's age, height, weight, and dominant leg was obtained as basic data. All subjects were confirmed to be able to perform single-legged standing with the left and right legs for at least 10 seconds and then to keep standing in tandem position for at least 30 seconds. In addition, proprioceptive sense (motion sense and joint position sense) of the ankle and great toe was tested manually and confirmed to be normal. For the analysis, the inclination angle of the non-dominant foot (target angle) was used as the set angle, and the angle at which the subject stopped the plate was used as the stop angle. The error (| set angle - stop angle |) was the test parameter. The minimum error value obtained in the two trials was recorded. In the analysis, the two groups were compared with respect to this error value. The statistical analysis was performed using SPSS (version 16). A t-test, one-way analysis of variance, and multiple comparison test were performed using a significance level of 5%.

Figure. 4. Experimental scene for evaluation of the ankle joint sense on themotion-driven foot plate.

III. Results

The minimum error between the target angle and the stop angle (absolute value) measured at different angles of the ankle positions (plantarflexion and dorsiflexion) in each joint movement with an angular velocity of 1 deg/sec are shown for the elderly group in Fig. 5. The error between the target angle and the stop angle measured at the different angles of the ankle positions in each joint movement tended to increase with greater target angle of the ankle position. A similar tendency was seen for the young subjects. In the elderly group, the error was significantly greater at the large angles of the ankle positions in each joint movement than at the small angles. The minimum error between the target angle and the stop angle at the different angles of the ankle positions in each joint movement with an angular velocity is shown for the two groups in Fig. 6. For each angle of the ankle positions, the error in proprioceptive sense was approximately 1.2-fold greater for the elderly subjects than

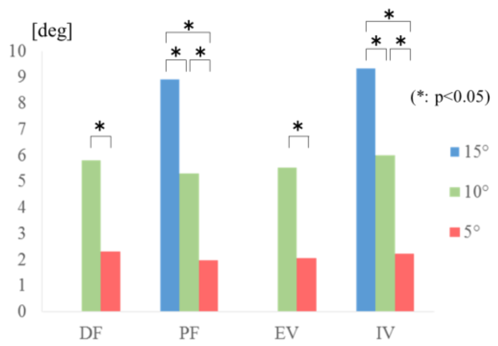

Figure. 5 The average of the minimum error between the target angle and the stop angle at the different angles of the ankle positions in the elderly group at the velocity of 1 deg/s.
(DF: Dorsi-flexion, PF: Planter-flexion, EV: Eversion, IV: Inversion)

for the young subjects. The difference was particularly

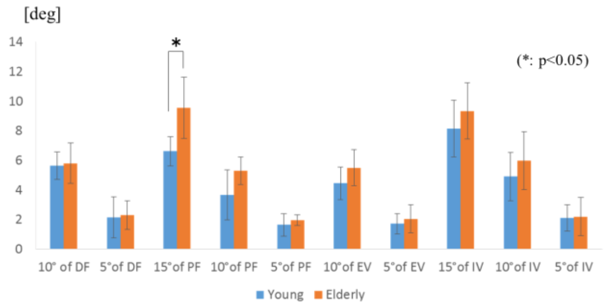

Figure.6 The average of the minimum error between the target angle and the stop angle at the different angles of the ankle positions in the two groups at the velocity of 1 deg/s. (DF: Dorsi-flexion, PF: Planter-flexion, EV: Eversion, IV: Inversion)

significant with 15 degrees of plantar flexion. With regard to the comparison to the angular velocities of 1 deg/sec and 2 deg/sec, the tendency for the error to increase was seen at the greater target angle of ankle position in both groups. In addition, in the young group, the error significantly increased with greater set angle with an angular velocity of 2 deg/sec as compared with 1 deg/sec in dorsiflexion, plantar flexion, and eversion in Fig.7. However, there was no significant difference between 2 deg/sec and 1 deg/sec in the elderly group except the data of 15 degrees of plantar flexion in Fig. 8.

IV. Discussion

A comparative analysis of the two groups using the measurement results obtained with the device suggested that the ankle proprioceptive sense of the subjects was affected by factors such as aging and the direction and velocity of joint movement. Previous reports have concerned differences in sensory input from the plantar surfaces and toes with age and their effect on standing balance [1, 2, 17], and studies have used a variety of sensory evaluation methods to examine ankle proprioceptive sense. However, very few studies have elucidated its effect on the quantitative ankle proprioceptive threshold associated with changes in the angle of the ankle, as in the present study.

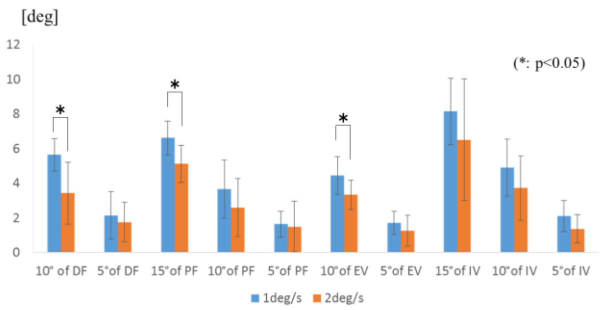

Figure.7 The average of the minimum error between the target angle and the stop angle at the different angles of the ankle positions in the young group in comparison of the velocity of 1 and 2 deg/s.
(DF: Dorsi-flexion, PF: Planter-flexion, EV: Eversion, IV: Inversion)

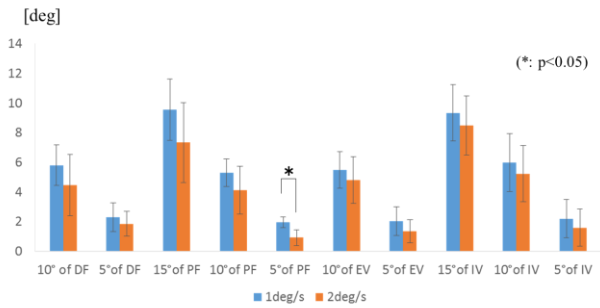

Figure.8 The average of the minimum error between the target angle and the stop angle at the different angles of the ankle positions in the elderly group in comparison of the velocity of 1 and 2 deg/s.
(DF: Dorsi-flexion, PF: Planter-flexion, EV: Eversion, IV: Inversion)

The results of this study showed that the decrease in ankle proprioceptive sense in elderly individuals varied with changes in dynamic joint movement during standing. The lower extremity joint movement strategies used during standing balance are known to vary [18]. The human body uses three strategies to maintain balance in the standing position: the ankle strategy, in which balance is maintained by activating the muscles that move the ankle; the hip strategy, which involves maintaining balance by activating the muscles of the hip joints; and the stepping strategy, which involves stepping with the legs to avoid falls [18]. The ankle strategy allows a quick reaction because the strength of the muscles around the ankles is used to move the point where the ground reaction forces are exerted against the plantar surfaces. However, this strategy is difficult for elderly individuals to execute [18]. To compensate, elderly individuals are said to often use the hip strategy, in which the body's center of mass is adjusted by bending the trunk and hip joints when, for example, the floor is unstable [18]. Regardless of how any of the three strategies is selected, somatosensory information from the plantar surfaces and ankles plays an important role in maintaining standing balance. Accordingly, increased error in ankle proprioceptive sense may worsen the sensory input needed for the ankle strategy and act as a factor that prompts a change of balance strategies.

The joint sense measurement method used in this study was implemented in the standing position with a load placed on the feet. Boyle et al. stated that the proprioceptors alone around the ankle that are involved in JPS cannot be isolated when performing measurements in the standing position because the antigravity muscles are affected by the neuromuscular control system [10]. They recommended using the sitting position to eliminate the effects of structures other than ankle. Konradsen et al. anesthetized the ligaments and articular capsule on the lateral side of the ankles of healthy individuals and found the joint position sense to be less prone to error when tested using an active evaluation method than when tested using a passive evaluation method, even though the proprioceptors had been anesthetized. Consequently, they surmised that the joint position sense depended on proprioceptive sense present in the muscles and tendons when examined using an active evaluation method and on proprioceptive sense present in the soft tissue around the ankle when tested using a passive evaluation method [13]. With the leg position used in the present study, the evaluation method could not be considered entirely passive because of the effects of the various joint muscle groups during standing. However, an objective of the present study was to measure ankle proprioceptive sense for the ankle strategy, which is important for standing balance in daily life, in order to facilitate training to prevent falls by elderly individuals.

The results of the analysis of the effects on ankle proprioceptive sense in the standing position in this study showed a tendency for joint sense error to increase with greater joint angle in joint movements except for ankle inversion. When the ankle strategy during standing balance is considered, this may have a greater effect on balance control in elderly individuals than in young individuals in cases where there is little visual information when standing or walking in circumstances such as an unstable road surface or steep hill. Consequently, comprehensive balance training that includes aggressive rehabilitation of the lower extremity senses as well as muscle strength training to prevent falls is important. Although the examination of the speed of joint movements showed that the error increased with faster movements, the difference was small between elderly individuals with the angular acceleration velocities used in this study. This indicated that the error may be large for elderly individuals regardless of velocity. Demonstrating this will require examination of a greater variety of joint movement velocities.

Fall prevention for elderly individuals in Japan has focused on muscle strength training of the sort typified by power rehabilitation. With our study, however, it is anticipated that awareness of the importance of the senses will increase in the future and that sensory training will be introduced into balance programs, which will yield benefits for fall prevention. We hope in the future to develop a device for joint training that can be applied to sensory testing and training that encompasses not only the ankles but also the knees and hip joints.

V. Conclusion

The device developed for this study can measure ankle proprioceptive sense, which is an important element of standing balance ability. The measurement results showed a tendency for the proprioceptive thresholds to increase with the change in the ankle joint angle with age. In the future, we hope to improve measurement accuracy by combining a variety of joint movement velocities and sensory evaluation methods and establish balance training techniques that use this device. In doing so, we hope to contribute to improving the balance ability of elderly and disabled individuals and to preventing falls.

ACKNOWLEDGMENT

The authors thank the subjects for their participation.

FUNDING

This work was partially supported by JSPS KAKENHI Grant Number JP24650346.

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