INTRODUCTION

Falls are a geriatric syndrome resulting from both physical and psychological problems and represent a serious concern for elderly people. Recovery from falls is often complicated by poor quality of life resulting from restricted mobility, functional decline, and increased risk of nursing home placement. The reported percentage of elderly people experiencing falls ranges from about 20–40% per year. In elderly people, falls leading to fractures can result in the patient becoming bedridden, which places an economic burden on society. Therefore, the prevention of falls is becoming increasingly important.

The evaluation of balance is important in the prediction of falls. Balance may be impaired by many factors, including muscle weakness, disturbed sensation, and restricted range of motion. The evaluation of these factors is important to inform therapy decisions, including the need for assistance. The Berg Balance Scale, the Functional Reach Test, and the Timed Up and Go Test are often used to evaluate balance. Teranishi et al. developed the Standing Test for Imbalance and Disequilibrium (SIDE), which focuses on the maintenance of static posture. SIDE is scored on an ordinal scale with six levels, each representing a specific ability. The postures evaluated using SIDE are wide base, narrow base, tandem stance, and one-foot stance. The total...
path length of the center of pressure (COP) was found to significantly increase as the area of the base of support (BOS) decreased. Using the SIDE level, complete separation of non-fall subjects was seen at level 2b and higher. Level 2b indicates that a subject can maintain a tandem standing position for more than 5 s on one side but not on the other.

Posture and center of gravity (COG) are important in balance and falls. Robinovitch et al. analyzed falls captured on video in long-term care facilities and found that the most common cause of falls was incorrect transfer or shifting of body weight, which they defined as a seemingly self-induced shifting of body weight that causes the COG to move outside the BOS. This suggests that the positional relationship between COG and BOS is important for falls. Tandem stance requires control of the mediolateral movement of the COG. Some studies have reported that tandem stance was useful in identifying individuals at risk of falls. In contrast, other studies have reported that tandem stance was not significantly related to falls. We believe that the evaluation of tandem stance, including the SIDE level, is limited by the lack of consecutive change in BOS. The change from semi-tandem or tandem stance to a crossed-leg posture involves the transfer of body weight, and incorrect transfer of body weight is involved in falls. The distance that the legs cross after moving from a static stance to a crossed-leg posture may be important in identifying individuals at risk of falls; however, this hypothesis has not yet been investigated.

In this study, we designed a new test to evaluate the ability to maintain a standing posture. The test involves measuring the inter-foot distance (IFD) during tandem stance. The purpose of the present study was to quantify the maximum IFD and the ability to maintain a standing posture in young healthy adults, which is an essential step before conducting the evaluation in elderly people.

**METHODS**

**Participants**

Thirty-eight healthy volunteers [17 men and 21 women; age 29 ± 6 years, height 163.3 ± 8.0 cm, weight 54.3 ± 9.4 kg (mean ± SD)] participated in this study. The presence of a severe orthopedic disorder was an exclusion criterion. The ethics committee of the National Center for Geriatrics and Gerontology approved this study. Written informed consent was obtained from all subjects before they were enrolled in the study.

**Equipment**

A three-dimensional motion analysis system using eight cameras (VICON MX, Vicon Motion Systems, Oxford, UK) and a split-belt treadmill (Tech Gihan, Uji, Japan) were used to collect data. The treadmill was equipped with two separately controlled belts. Force plates (size: 320 mm × 1200 mm) were positioned under each belt. Motion analysis data and force plate data were synchronized and collected at 100 Hz on a personal computer.

**Procedure**

The subjects wore socks under the assumption of indoor activity, and a reflective marker (14-mm diameter) was attached to the sock over the head of the first metatarsal on each foot. The subjects were instructed to stand on the treadmill belts facing perpendicular to the direction of belt motion. They stood with both feet on the rear belt with their feet placed shoulder-width apart, and then moved one foot forward onto the front belt. Once in this position, they were instructed to cross their arms over their chest. Each subject wore a harness (Moritoh, Ichinomiya, Japan) to prevent falls. They stood with both feet on the rear belt with their feet placed shoulder-width apart, and then moved one foot forward onto the front belt. Once in this position, they were instructed to cross their arms over their chest.

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**Data Analysis**

The maximum IFD was normalized by subject height and multiplied by 100. The mean value of the five trials was calculated for each condition. The data were then analyzed using two-way analysis of variance (front leg × belt velocity).
RESULTS

The normalized maximum IFD values are shown in Table 1 and Fig. 2. Figure 3 shows an example of the time course data of the load on the dominant foot and on the non-dominant foot and the IFD. There was no significant interaction between the front leg and belt velocity (P=0.42). There was a significant main effect of the front leg on the normalized maximum IFD: the normalized IFD was larger when the dominant foot was in front than when the non-dominant foot was in front (P=0.044). There was no significant main effect of the belt velocity on the normalized maximum IFD (P=0.97).

The number of times that the rear leg was removed from the treadmill belt was 8 in 760 trials (38 persons × 4 conditions × 5 trials). Three times out of eight, the dominant foot was removed from the treadmill belt.

DISCUSSION

Static tandem stance is often used to evaluate balance, but the use of dynamic tandem stance has not previously been reported. We used a split-belt treadmill to investigate the relationship between the normalized maximum IFD and the ability to maintain a standing posture when the front foot was allowed to move with the treadmill belt.

The normalized maximum IFD was significantly larger when the dominant foot was placed in front. The dominant foot was defined as the foot that would be used to kick a ball. Therefore, we believe that the non-dominant foot played a major role in supporting the body.

Jonsson et al. measured tandem stance for 30 s using ground reaction forces recorded from force plates. Initially, the subjects stood with each foot on a force plate. To position themselves in tandem stance, the subjects then moved one foot to a force plate in front. During tandem stance, the vertical ground reaction force was twice as large for the rear leg as for the front leg. Teranishi et al. reported that the COP...
was located on the rear foot in tandem stance. In a review of the dominant hand and foot, the primary function of the dominant and non-dominant lower limbs was characterized as mobilization and stabilization, respectively. These results suggest that in tandem stance it is easier to control posture when the non-dominant foot is to the rear than when the dominant foot is to the rear. In the present study, the rear leg in tandem stance played a smaller role in supporting the body than would be observed in normal tandem stance because subjects were instructed to distribute their weight to both legs equally. However, just before stepping at maximum IFD, the function of the rear leg in supporting the body...
was of similar importance to that in normal tandem stance. Therefore, the normalized maximum IFD was significantly larger when the dominant foot was in front than when the non-dominant foot was in front.

There was no significant main effect of treadmill belt velocity on the normalized maximum IFD. Maki et al. described two strategies that can be used to control posture: fixed-support and change-in-support strategies. Fixed-support strategies involve control of the movement of the center of mass over an unchanging BOS, which is defined by the feet, and include an ankle strategy and a hip strategy. Change-in-support strategies involve stepping or grasping movements that serve to alter the BOS. Fixed-support strategies might be important in providing an early defense against loss of balance; however, change-in-support strategies have the potential to make a much larger contribution to stabilization. In the present study, we investigated the maintenance of posture while IFD changed before stepping. Therefore, the definition of change-in-support strategies is different from the present strategy in terms of step timing. The strategy of the present study is also different from the definition of the fixed-support strategy because the BOS changed and the load on one leg was gradually reduced.

In the present study, the movement of the feet was similar to that of crossover steps, insomuch as the IFD reached zero and the legs crossed. In one previous study, subjects were instructed to walk straight ahead for about 4 m to reach a “turning zone”, and then turn onto a designated path that was at an angle of 45° or 90° and keep walking until they reached a pylon positioned at the end of that path. The step velocity in healthy elderly people was about 3.6 km/h. However, crossover steps were not distinguished from side steps, and the velocity of any crossover steps was not reported. As a fall evaluation, Yungher et al. measured the short-term changes of protective stepping following waist-pull perturbations in the mediolateral direction. In that study, the crossover stepping velocity was about 2.9 km/h, assuming that the average leg length of the participants was 85 cm. However, the belt velocity in the present study was much slower than that used in clinical practice and in the abovementioned previous studies. In the current study, we were more interested in the relative positions of the feet than in the velocity of the feet. In a pilot study, we observed that many subjects could not maintain a standing posture just after the treadmill belt started to move at 1.5 km/h. Accordingly, we could not include the effect of belt velocities of 1.5 km/h or greater or investigate the relationship between belt velocity and IFD at velocities above 1 km/h. We speculate that the reason there was no significant main effect of treadmill belt velocity on the normalized maximum IFD was that the belt velocity was much slower than the velocity of the feet that leads to falls. A future study should set a faster belt velocity than that of the present study.

Some limitations to the present study should be considered. First, the belt velocity was much slower than the velocity of the feet that leads to falls, as discussed above. Second, COG and COP were not investigated. We assume that the normalized maximum IFD is related to COG and COP; however, that hypothesis remains unproven. Third, we studied only young healthy subjects and did not study any patient population or elderly people with poor balance. Moreover, the number of subjects was small, and the study was performed in the department of one institution. Future studies should aim to investigate several tasks using normalized maximum IFD, to vary the treadmill belt velocity and inclusion criteria, to include COG and COP, and to compare young subjects to patient populations with poor balance and frail elderly persons.

In summary, we quantified the normalized maximum IFD when the BOS in standing posture was changed in healthy subjects. The results provide new information that the legs can cross by 10–12% of the height while maintaining posture. The normalized maximum IFD was significantly affected by which leg was placed in front, but was not significantly affected by the treadmill belt velocity. In future studies, with the aim of preventing falls, we would like to quantify the normalized maximum IFD in this paradigm in frail persons and quantify the relationship with falls.

**CONFLICTS OF INTEREST**

The authors declare that there are no conflicts of interest.

**REFERENCES**


