

Analysis of obstacle height threshold for elderly to safely cross based on dynamic stability

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Abstract. To calculate the threshold of obstacle height that could ensure the safe crossing of the elderly. The conventional kinematics parameters, TO moment, and temporal dynamic parameters were involved. The dynamic stability parameters of the young group, the elderly group, and the fall group were calculated under the 5m-25cm obstacle gait. Both kinematic and dynamic stability parameters can reflect the changes in dynamic stability with aging. Still, only the temporal dynamic stability parameter can significantly distinguish the detailed differences between the elderly group and the fall group, and this difference occurred only when the height of the obstacle reached 20cm. This study calculates the height threshold for the elderly to safely cross obstacles, which can guide the aging adaptation of related facilities.

Keywords: Stumble; Age-friendly; Dynamic Stability analysis; Obstacle height threshold.

1. Introduction

Falls are a major health problem in the elderly. 30% of the elderly over 60 years old and 50% of the elderly over 85 years old fall at least once a year [1,2], while 4%-5% of the elderly in China fall 2-3 times in a year [3]. According to the different causes of instability, falls can be divided into tripping, slipping, and falling. Among them, about 33% to 53% of elderly falls are caused by the failure to pass through the bumps or obstacles on the ground [4,5]. At the same time, tripping is also the main cause of fracture in the elderly, among which hip fracture is the most serious type of injury, which is significantly related to the incidence, mortality, and loss of living ability of the elderly. It brings a heavy economic burden to the elderly family and even society [6].

The study of gait stability across obstacles in the elderly is of great significance for the prevention of falls in the elderly. Crossing obstacles is a difficult and dangerous behavior that often occurs in the elderly. Improper handling is easy to lead to falls. Some studies have pointed out that falls in the elderly are directly related to abnormal gait across obstacles, and tripping is believed to be caused by the inability of the elderly to adjust their gait and posture in time after the support surface is disturbed [7]. This study further proposes the hypothesis that abnormal gait across obstacles in older adults may be associated with decreased control over obstacle behaviors.

From the perspective of motion mechanics, a fall is essentially an instability phenomenon [8], including three stages: the imbalance caused by the body's center of mass exceeding the stability boundary, the weightlessness caused by the failure to adjust the body posture in time, and the touchdown collision at the moment of the fall [9]. Decreased stability directly affects the balance ability of the human body, which is easy to cause imbalance, and then induces chain reactions such as weightlessness and touchdown collision, which is one of the direct causes of falls in the elderly [10]. In recent years, researchers have proposed and developed the dynamic stability control theory [11,12]. Compared with the traditional static stability control theory, the dynamic stability control theory regards the relationship between the position-velocity interaction of COM and the Base of Support (BOS) as an index to measure the stability of the human body. It has deepened the understanding of the mechanism of human stability control, which can better explain the imbalance

and rebalance in the process of human movement and has important guiding significance for the fall risk assessment and intervention of the elderly [13].

However, current studies of dynamic stability based on the velocity stability domain are still limited TO special moments such as TO or HS of the single-supported phase. As we know, gait is a continuous process, and a single special moment is not enough to reflect the situation of a single support phase. It is urgent to analyze the dynamic stability of the complete period of a single support phase based on the previous research on the multi-dimensional dynamic stability of the special moment and optimize the parameters of the velocity stability domain as a time sequence variable. The time dimension was extended to further improve the dynamic stability analysis method based on the velocity stability domain.

In summary, based on dynamic stability method research, this paper will collect gait stability data of the elderly when crossing obstacles of different heights, study the influence of obstacles of different heights on the gait stability of the elderly, analyze the obstacle height threshold that can ensure the elderly to cross smoothly, and provide support for the age-friendly design of related facility heights.

2. Experiment

2.1 Participants

Thirty people participated in the study, involving ten healthy young (Young: 22-29 years old), ten healthy elderly (Elderly: 63-79 years old), and ten elderly with a history of stumbles (Faller: 61-79 years old). The criterion for inclusion in the Faller category was a self-report of tripping once or more within the past three months [14]. The participants reported no history of neurological pathology, head trauma, vestibular dysfunction, or any disease that may be dangerous during the experiment. Written informed consent was collected before testing. The experimental protocol was approved by the Office of Research Ethics.

2.2 Test Configurations

Experimental measurements were composed of (1) a motion analysis system with 15 cameras (Motion Analysis Corp., Santa Rosa, CA, USA, displacement error $\leq 0.1\text{mm}$) to capture three-dimensional kinematic gait information; (2) plantar pressure acquisition (Tekscan Matscan, Tekscan Inc., South Boston, USA) to collect pressure distributions underneath the foot, with sensor spatial resolution of 4 sensels/cm²; (3) A series of obstacles for single-obstacle crossing testing, including 5cm, 10cm, 15cm, 20cm and 25cm.

2.3 Protocol

The participants were dressed in experimental tights and antiskid socks, with a total of 26 reflective markers defining a 15-segment model, in addition, markers were also set on both ends of each obstacle to calculate the relevant distance. Each participant was collected three times, and the movement data acquisition frequency was 60Hz. If the obstacle was touched off, the data acquisition was restarted. All data were smoothed using a fourth-order Butterworth low-pass filter with a cut-off frequency of 6 Hz.

3. Methods

In this article, toe-obstacle distance (TOD), heel-obstacle distance (HOD), toe-obstacle clearance (TOC), Region of Velocity Stability in 2-D at TO (ROSVTO2-D), Fréchet Distance of ROSv in 2-D (ROSVFD2-D), and Shannon Entropy of ROSv in 2-D (ROSaSE2-D) were involved. All the calculated results were analyzed by one-way ANOVA or Kruskal-Wallis/Wilcoxon non-parametric test (SPSS ver 20). The significance level was $p = 0.05$.

A single-link-plus-foot inverted pendulum model was applied to calculate parameters, and the frame of maximum velocity in the vertical direction of the middle segment of the left foot was defined as the TO moment. The right leg single stance period was examined, of which left TO was determined when the vertical velocity of the left midfoot reached maximum [15]. Woltring’s generalized cross-validated spline algorithm was used to acquire smoothed COMv [16].

Markers on participants and obstacles were used to calculate toe-obstacle distance (TOD), heel-obstacle distance (HOD), and toe-obstacle clearance, respectively (TOC) [17]. The whole-body COM was calculated as the weighted sum of 15 body segments [18]. The calculation methods of ROSv2-D were referred to in the previous research [19,20].

the Fréchet distance between the participant’s sample curve and the standard curve in 2-D was calculated as ROSvFD2-D. The ROSa curve was obtained by differentiating the ROSv curve, and the ROSa Shannon entropy was obtained by Multifractal Analysis. Assuming that the ROSa curve of the participant was a continuous random variable, its instability can be expressed by Shannon entropy.

4. Results

With the increase in age, the TOD of participants tended to decrease (Fig. 1(a)). When the obstacles were low, the trend of HOD with age was not obvious (Fig. 1(b)). As the height of the obstacle increases, the HOD of the young group showed a significant difference compared with the two older groups. When crossing obstacles, TOC changed significantly with age (Fig. 1(c)). When the obstacle height was low, TOC increased significantly with age. When the obstacle height increased, TOC showed an opposite trend.

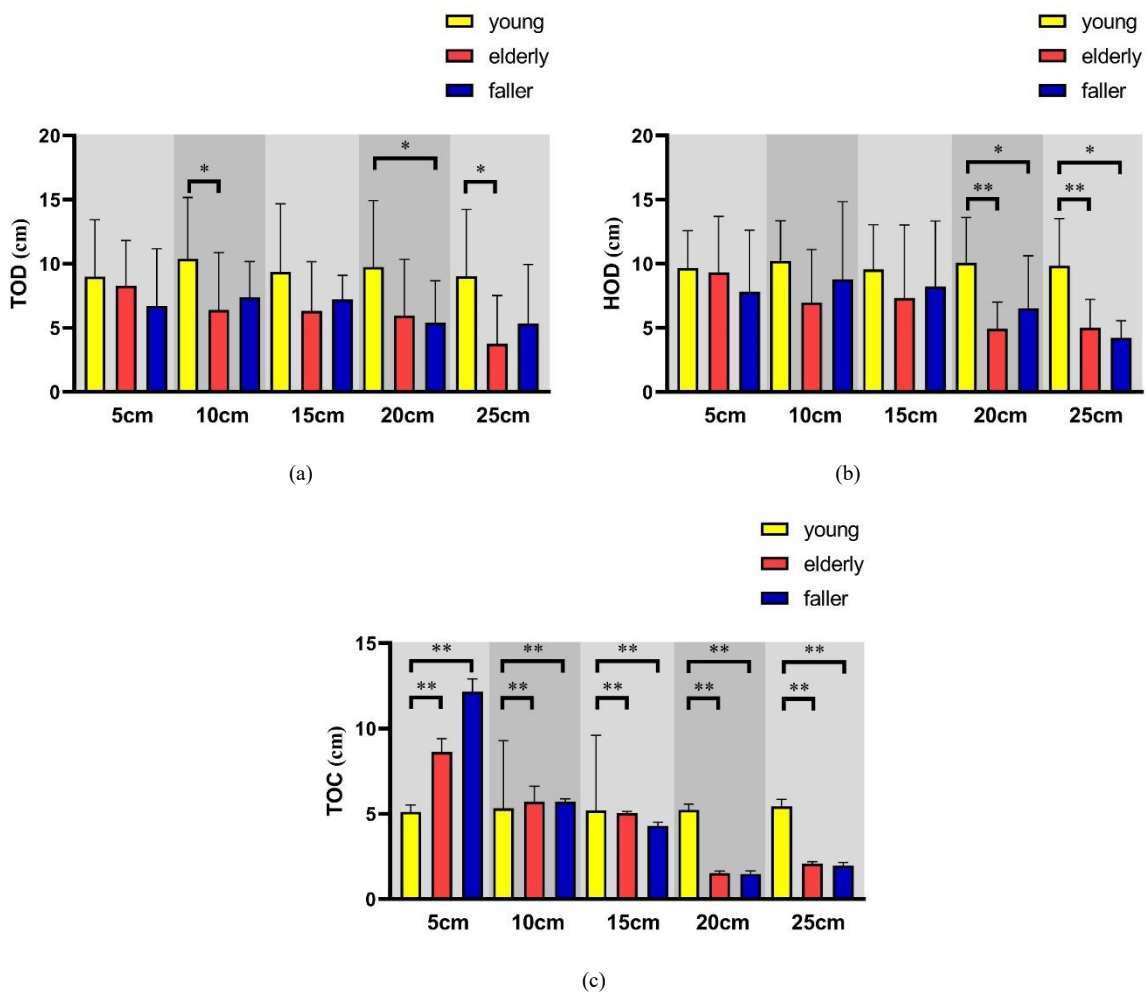


Fig. 1 Kinematics parameters in each group with the increase of obstacle height, Kinematics parameters included (a) TOD, (b) HOD, and (c) TOC. (* $p < 0.05$, ** $p < 0.001$).

ROsv2-D at TO showed that, with the increase of age, the distance between the standardized COM velocity - position and the standard curve became closer, and the difference between groups was significant (Fig. 2).

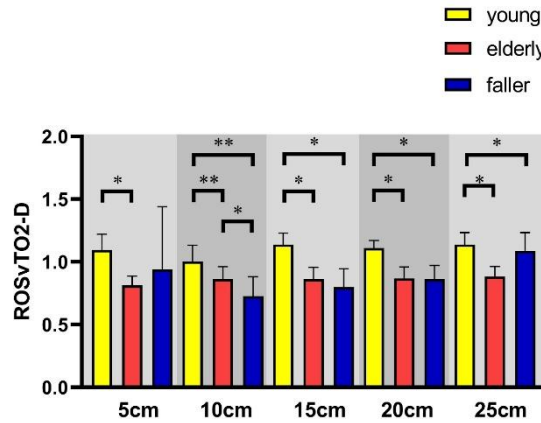


Fig. 2 ROSv2-D at TO in each group with the increase of obstacle height. (* $p < 0.05$, ** $p < 0.001$).

The two-dimensional ROSv results of the single support phase calculated based on Fréchet distance indicated that ROSvFD2-D showed a significant increasing trend with age and the influence of tripping history (Fig. 3(a)). 20cm, the young group (1.02 ± 0.09) was significantly smaller than the elderly group (1.52 ± 0.17 , $p < 0.001$) and the fall group (1.69 ± 0.47 , $p < 0.001$), and the elderly group was significantly smaller than the fall group ($p < 0.05$).

The 2-D ROSa calculated based on Shannon entropy also showed similar results (Fig. 3(b)). 20cm, the young group (2.81 ± 0.32) was significantly smaller than the elderly group (4.62 ± 0.90 , $p < 0.05$) and the fall group (5.31 ± 2.12 , $p < 0.001$), and there was also a statistically significant difference between the elderly group and the fall group ($p < 0.05$).

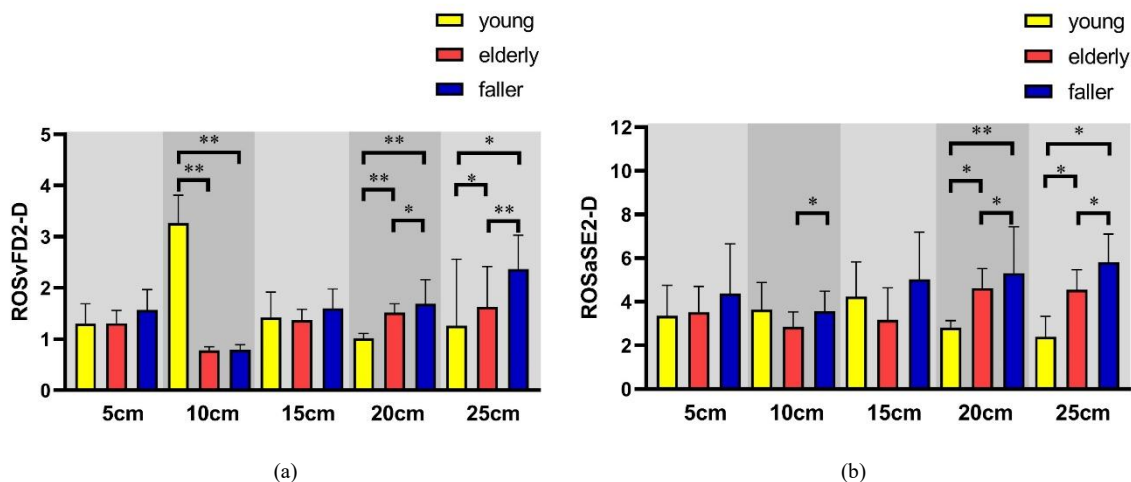


Fig. 3 ROSvFD2-D and ROSvSE2-D in each group with the increase of obstacle height. (* $p < 0.05$, ** $p < 0.001$).

5. Discussion

With the increase in age or the occurrence of tripping, the dynamic stability of gait across obstacles will decrease correspondingly, and the risk of tripping will increase too. In this paper, we investigated the performance of traditional kinematic parameters, single moment, and

time-sequence dynamic stability parameters in young, old, and fall groups. The dynamic stability of each group when crossing obstacles of different heights was also analyzed.

In general, the traditional kinematic parameters can distinguish the age-induced differences in dynamic stability across obstacles to some extent, and this difference also tends to be more significant with the increase in obstacle height. In the case of TOD, when the obstacle height was small, the difference between the fall group and the young group was not significant. However, when the obstacle height reached 20cm, the fall group was significantly smaller than the young group. This may be related to the fact that the dynamic stability of subjects in the fall group has already decreased, and when the height of obstacles exceeds the height threshold for maintaining dynamic stability, the risk of tripping will increase [7]. HOD also showed similar results, and 20cm was again the turning point at which the significant difference between the fall group and the young group appeared. This may be related to shorter step lengths and shorter distances between feet and obstacles in the fall group [21]. The results of TOC were somewhat special. From the obstacle height of 5cm to 25cm, TOC showed significant differences with age. What is different is when the obstacle height was less than 15cm, TOC increased significantly with age. However, when the obstacle reached more than 15cm, TOC decreased significantly with age. By lateral comparison of the TOC results in each group at different heights, it was found that no matter the height of the obstacle, the TOC of the young group was maintained at about 5cm, that is, with the change of the obstacle height, the leg raising height of the young group with stronger dynamic stability control ability would also change accordingly. On the contrary, the fall group ignored the change in the height of the obstacle. When the swing leg was above the obstacle, the height from the ground was about 20cm. When the obstacle was higher than 20cm, there was a risk of tripping. It may be related to the fact that older people need a longer time to perceive postural changes with the increase of somatosensory threshold [22]. It also reflects the decline of dynamic stability of subjects in the fall group from the side. To ensure safe crossing of obstacles, when the height of obstacles is low, the conservative dynamic stability posture of high leg raising is still selected. However, although the traditional kinematic parameters reflect the differences in dynamic stability with aging, they cannot distinguish the differences in body posture control ability between the elderly group and the fall group.

ROSv is the velocity dynamic stability domain during walking and represents the ability of the human body to control dynamic stability. The two-dimensional ROSv at TO results showed that the two older groups were closer to the stability boundary than the younger group. The results showed that the two elderly groups were more inclined to place the COM close to the toe support point to obtain more effective static support and ensure stability defensively, while the COM of the young group was relatively far away from the toe support point, and it was driven by forward inertia. In comparison, to maintain the dynamic stability of gait, relying on static support requires stronger lower limb muscle strength as an objective support, and it also needs to consume more energy during walking. For the elderly, the above requirements cause a greater burden for stable walking and increase the possibility of falls. Although ROSvTO2-D significantly distinguished the difference in dynamic stability between the elderly group and the fall group in the walking gait [19], there was no significant difference in ROSv at the time of TO between the two groups in the obstacle-crossing gait. It may be related to the fact that the dynamic stability at the TO cannot replace the dynamic stability at the time of crossing the obstacle.

Since the Fréchet distance method is more efficient in evaluating the similarity of curves with a certain spatial and temporal order, we proposed to apply this method to the similarity analysis of ROSv curves. When the obstacle reached 20cm, there was a significant difference between the fall group and the elderly group, and the fallers had a significantly higher ROSvFD2-D than the elderly group and the young group. Since the basic principle of Fréchet distance is to calculate the difference between the sample curve and the standard curve, the larger the value, the worse the dynamic stability, the analysis results based on ROSvFD2-D showed that the dynamic stability of the fall group was significantly weaker than that of the other two groups when crossing the obstacle.

The acceleration index can not only reflect the influence degree of different momentum control abilities on dynamic stability more sensitiveness but also reveal the mechanism of the elderly who are prone to fall while walking due to the decline of skeletal muscle control ability [23]. Besides, since Shannon entropy can express the degree of uncertainty or chaos more accurately, it is proposed to use this method to analyze the ROSa curve fluctuation problem in this study. Similar to the results of ROSvFD2-D, when the obstacle height reached 20cm, reflecting the difference in dynamic stability caused by aging, the ROSvSE2-D parameters also showed statistically significant differences between the fall group and the elderly group. Moreover, the ROSvSE2-D of the fall group was significantly higher than that of the elderly group and the fall group. Considering that the more severe the fluctuation of the curve, the worse the control ability of human momentum and stability, that is, the dynamic stability of the fall group was significantly weaker than that of the other two groups. In a word, based on the analysis of time-series dynamic stability parameters, 20cm may be the height threshold for the elderly to smoothly cross obstacles.

In conclusion, this study analyzed the dynamic stability of young, elderly, and fall groups during obstacle-crossing gait using traditional kinematic parameters, ROSv parameters at TO, and temporal ROSv parameters. The time-domain ROSv parameters may be more sensitive to reflect the difference in dynamic stability caused by tripping, and 20cm may be the height threshold for the elderly to safely cross obstacles, which can guide the design of age-appropriate facilities. This paper only analyzed the changes in the dynamic stability of different subjects during single obstacle crossing. It will add the dynamic stability analysis of continuous obstacles in the future, to analyze the various complex situations of elderly people crossing obstacles more accurately.

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