Risk of Tripping, Minimum Foot Clearance, and Step Length When Crossing a Barrier

**Abstract**

This study was designed to investigate gait parameters upon crossing a barrier and environmental factors influencing the perceived risk of tripping. These factors included illumination and barrier conditions. Barrier conditions were divided into height, type, and color of the barrier. Illumination conditions included normal and dimmed conditions. Twelve male participants were recruited. They walked on a walkway, moving over a barrier. They gave a subjective rating of risk of tripping (SRRT) both before and after the walk. A research assistant recorded a gait disturbance rating (GDR) based on his observation of the gait of the participant upon barrier crossing. The minimum foot clearance (MFC) of both the leading and lagging foot when moving over the barrier, and the step length of the participant before and after crossing the barrier were calculated. The results indicated that the SRRT, both before and after the walk, was significantly (*p*＜0.0001) higher when the barrier height increased. Increased barrier height caused significantly (*p*<0.0001) higher GDR. The barrier type (*p*<0.01) and illumination conditions (*p*<0.001) had significant effects on the MFC of both the leading and the lagging foot. The color (*p*<0.05) and height (*p*<0.05) of the barrier also influenced the MFC of the lagging foot significantly. Step length of the leading foot when crossing the barrier was significantly affected by illumination condition (*p*<0.001) and barrier type (*p*<0.05). The results of the study are helpful in understanding the mechanisms brought into play when moving over barriers on walkways. They provide meaningful information that will help in reducing trip and fall accidents.

**Keywords**

trips & falls; risk of tripping; foot clearance; step length; barrier crossing

1. Introduction

Falls are common both in daily life and at work. They have led to unintentional injuries globally (Hsieh et al., 2020; Hsu, 2016; Li et al., 2019a; Wadhwaniya et.al., 2017) and have caused huge economic losses to individuals and society (Amandus et al., 2012; Ramaswamy & Mosher, 2018). The proportion of falls among all types of injury around the globe increased from 23.1% in 1997-2007 to 27.7% in 2007-2017 (James et al., 2018). In Taiwan and the United States during the period 2009 to 2018, the proportions of falls at work rose from 15.82% to 21.21%, and from 24.35% to 26.97% of all occupational injuries, respectively (BLS, 2019; OSHA, 2019). Falls occur because of slips, trips and loss of balance, among other reasons. The literature has shown that tripping and slipping are the main contributors of falls (Bentley & Haslam, 1999; Berg et al., 1997). Tripping has been considered one of the main precedent events that leads to falling for the elderly. More than a third (35% to 47%) of elderly falls occur because of tripping (Berg et al., 1997; Overstall et al., 1977). Thus, studying the mechanisms and influencing factors in tripping will contribute significantly to efforts to improve the safety of both the public and workers.

Previous studies have shown that the factors causing tripping can be divided into two groups: unsafe environments and unsafe behaviors (Huang et al., 2013; OSHC, 2018). Poor lighting conditions and improper gait patterns when negotiating a barrier are examples of unsafe environments and behaviors, respectively. Vision, affected by illumination condition, has an influence on the stability of gait (Hallemans et al., 2010; Logan et al., 2010). Visual information can help pedestrians to control their limbs when moving over barriers (Patla & Vickers, 1997; Patla & Greig, 2006). A person with poor vision may not see floor conditions clearly and hence has a higher probability of tripping. Patla and Greig (2006) found that the probability of tripping could reach as high as 53% when walkers’ views of floor conditions are blocked. Illumination is an environmental factor affecting vision and thus the risk of tripping. The literature has indicated that the risk of tripping in a dimmed environment is 15.5 times that under normal illumination conditions (Li et al., 2019b). A pedestrian, for example, will not be able to visually spot a pavement barrier if illumination is lower than a threshold value (Fotios and Uttley, 2018).

In addition to illumination condition, walking speed also has an influence on pedestrians' ability to avoid obstacles in their path. Pedestrians may not have enough time to adjust their gait when moving over a barrier at a fast pace and this may lead to tripping and falling. Walking speed upon moving over a barrier on the road affects the gait pattern of the walker. The literature has shown that flexions of the hip, ankle and knee increase significantly with increased pace when moving over a barrier (Draganich & Kuo, 2004; Schulz, 2011).

Obstacles on the ground are surely undesirable. Berard and Vallis (2006) requested their subjects to walk over one or two barriers in their path. They measured the distance between the toe and the barrier when moving over the barrier(s) and found that this distance in the two-barrier condition was shorter than that in the one-barrier condition. Lowrey et al. (2007) measured the time taken by participants to move across barriers. Their results showed that the time to cross the second barrier when there were two barriers was longer than that to cross only one barrier. For barrier height, Garman et al. (2015) found that the probability of tripping was positively correlated with barrier height. In other words, high barriers lead to a high probability of tripping. Chou and Draganich (1997, 1998) explored the influences of barrier height on gait parameters of the trailing foot. They found that the flexion angles of the hip and knee increased significantly (*p*<0.001) with barrier height when the toe of the trailing foot was above the barrier. The stance time of the trailing foot during the crossing step also increased significantly (*p*<0.0001) when the barrier height was raised. Similar results have been reported by Pan et al. (2016).

Age and physical condition can influence the risk of tripping when crossing a barrier. The literature (Huang et al., 2008; Novak and Deshpande, 2014; Ribeiro et al., 2019) has shown that older participants have lower center of pressure velocity of the stance foot and lower peak foot velocity when the toe is above the barrier than younger ones. Older adults, therefore, are more likely to trip than their younger counterparts. In addition, the literature has found compensatory mechanisms of the intact leg in the gait of lower limb amputees (Silverman et al., 2008; Harandi et al., 2020). Individuals with asymmetric gait patterns in their lower limbs have more difficulty passing over obstacles on the ground and thus are at greater risk of tripping.

Trips and falls may occur if a walker does not have sufficient foot clearance when stepping over a barrier. One of the kinematic parameters important in discussing risk of tripping (RT) is minimum foot clearance (MFC) (Begg et al., 2007; Benson et al., 2019; Carter et al., 2020; Garman et al., 2015; Loverro et al., 2013). This is the minimum space between the lowest end of the foot of the swing leg and the ground or the top of a barrier (Winter, 1991). When the minimum space occurs at the toe, it is also called the minimum toe clearance (MTC). In other words, the MTC is the shortest distance between the lowest end of the front part of the shoe/foot and the floor or a barrier (Khandoker et al., 2007; Schulz, 2017). Determining the MTC (or MFC) is important in measuring the risk of tripping especially for barrier crossing. Schulz (2011) found that the MTC not only doubled with the presence of a visible barrier, but also increased significantly with faster walking speed.

In addition to the kinematic parameters, subjective rating of risk of tripping (SRRT), also called perceived risk of tripping, has been used to estimate RT. Li et al. (2019b, 2020) have shown that the SRRT is significantly affected by lighting condition and barrier characteristics, specifically, its type, height, and color. However, they did not examine the effects of lighting condition and characteristics of the barrier on the MFC. Our hypothesis was that type, height, and color of the barrier, and illumination condition were all significant factors affecting both the MFC and step length upon barrier crossing. Our purposes in this study were to test these hypotheses so as to increase our knowledge of the kinematic mechanisms involved in tripping accidents. SRRT data and step length before and after crossing the barrier were also investigated to provide a more complete picture of gait behaviors in barrier crossing.

2. Materials and Methods

We conducted the gait experiment in a laboratory where the temperature and humidity were 19.0 (±4.6)℃ and 59.9 (±9.1)%, respectively.

2.1 Human participants

Twelve healthy male participants without a history of musculoskeletal disease joined this study. Their age, body height, and body weight were 19.8 (±1.8) yrs, 174.3 (±5.2) cm, and 67.2 (±10.0) kg, respectively. Their visual acuities were measured using a vision chart (Miao et al., 1983). The decimal corrected visual acuities of the left and right eyes of the participants were 0.78 (±0.41) and 0.70 (±0.39), respectively. Before joining the experiment, the participants were instructed about the purposes and procedure of the experiment. They then read and signed an informed consent form. A local review board for human participant protection approved this study (Jen-Ai Hospital, JAH109-46).

2.2 Walkway and Barriers

Selection of walkway and barriers followed the protocol established in the literature (Li et al., 2019b). A walkway 6 m long was prepared. The floor of this walkway was covered with dark gray ceramic tiles. Two types of barrier were tested. One was a steel stick (Ø0.8 cm) 80 cm long. The other was a wooden board with a length of 60 cm and a thickness of 1.5 cm. Two exemplars of both the stick and board were prepared. One was a dark gray, the same color as the floor surface. The other was white. The high contrast of the white stick and board, as compared to the minimal contrast of the gray stick and board, made them much more easy to see.

Stick and board barriers with a height of 5, 10, or 15 cm were tested. For stick barriers, we placed two stands by the walkway to support the stick (see Figure 1). For board barriers, we placed a board on the walkway approximately 3.5 m from the beginning of the walkway. Both the stick and board barriers were light and easily moved. This was done so that participants would not trip and fall even if their feet touched the barrier.

Figure 1. here

2.3 Illumination conditions

The experiment was performed under two illumination conditions: normal and dimmed. The normal condition, with all the fluorescent lights in the laboratory turned on, was a lighting level typical for office work in local institutions. The dimmed condition, on the other hand, was simulated by blocking all the windows and turning off all the lights, except for the red LED lights on the cameras of the motion tracking system. The illuminance of six spots near the barrier on the floor was measured using an illuminance meter (TES-1336A; TES Electrical Electronic Corp., Taiwan). The illuminance for the normal and dimmed conditions was 169.4 (±3.7) lx and <0.01 (±0.0) lx, respectively.

2.4 Motion Tracking System

A motion tracking system (VICON, T40S, UK) was adopted to capture the motion of the feet of the participants. This system included eight cameras. The 3D coordinates of this system were established and calibrated. The filming rate was 100 Hz. Retroreflective markers (Ø1 cm) were fixed on the ankles and shoes of the participants (see Figure 2). The markers on the shoes were attached on the edges in the forefront and the heel, and on the top front of the metatarsals of the big and pinky toes. The 3D coordinates of these markers were captured to determine the MFC and step length before and after moving across the barrier.

Figure 2. here

2.5 Experimental Procedure

Before the experiment, a research assistant explained to the participants that trials would be carried out in normal and dimmed conditions. They would wear a pair of rubber-soled shoes and walk on the walkway with a barrier. The order of the illumination conditions, barrier types, barrier heights, and barrier color was randomly determined.

In the normal illumination condition, the participants stood at the starting point of the walkway. They observed the walkway and rated the risk of tripping (SRRT) on a scale from 1 - no risk to 5 - extremely high risk. This rating was marked SRRTb. The participants then walked toward the end of the walkway at a pace of 110 step/min following the sound of a metronome. The 3D coordinates of the reflective markers on their ankles and shoes were captured. After the walk, the participants rated the risk of tripping again, based on their experience of barrier crossing, using the same scale as in the SRRTb. This rating was recorded as SRRTa. A gait disturbance rating (GDR) was recorded by a research assistant based on his observation of the gait of the participants upon barrier crossing using the scale: 1- no disturbance: walked smoothly, 2- slight disturbance: walked slowing down slightly, 3- medium disturbance: walked slowing down markedly, 4- serious disturbance: stopped shortly before the barrier to adjust gait, and 5- foot-barrier contact. Foot-barrier contact implies the onset of tripping.

In the dimmed condition, the participants, wearing an eye mask, were led into the laboratory by a research assistant. The participants removed the eye mask, followed the same procedure wearing the lab shoes and stood at the starting point of the walkway and waited for approximately ten minutes for dark adaptation to take place. They then reported their SRRTb after observing the pathway. Then, the participants followed the same procedure walking along the walkway as in the normal illumination condition.

The MFC values were measured using the 3D coordinates of the foot markers (see Figure 3). The vertical distances from the toe and heel of the leading foot to the top of the barrier when crossing the barrier were calculated. The minimum of these two values was recorded as the MFClead. The vertical distance from the toe of the lagging foot to the top of the barrier when crossing the barrier was also calculated and was termed MFClag.

Figure 3. here

The step length of five steps before and after crossing the barrier were calculated using the 3D coordinates of the markers on the heel (see Figure 3). Step 3 length (ST3) was the distance from the heel of the leading foot to the heel of the lagging foot when crossing the barrier, which occurred when the leading foot had just passed the barrier and the lagging foot was still behind. Step 1 (ST1) and 2 (ST2) lengths were the step length of two and one steps before crossing the barrier, respectively. Step 4 (ST4) and 5 (ST5) lengths were the step length of one and two steps after crossing the barrier, respectively (see Figure 4).

Figure 4. here

2.6 Data Analysis

Every participant walked under 24 experimental conditions (3 barrier heights × 2 barrier types × 2 barrier colors × 2 illumination conditions) and was tested twice under the same experimental condition. There were, therefore, a total of 576 trials. Means and standard deviations of all the variables were calculated. The Kruskal-Wallis test and Wilcoxon rank sum test were performed on all the SRRT and GDR data to examine the significance of the variables comprising the experimental conditions. Analysis of variance (ANOVA) and Duncan’s multiple range test were performed on MFC and step length data. The SAS® 9.0 (SAS Institute Inc., Cary, NC) software package was used for statistical analysis. A significance level of α=0.05 was adopted.

3. Results

3.1 Subjective Ratings

Figure 5 shows the SRRTb statistics for the experimental conditions. The Kruskal-Wallis test results reveal that the SRRTb were significantly affected by barrier heights (*p*<0.0001). The SRRTb of the 5 cm condition (1.15±0.39) was significantly (*p*<0.05) lower than that of the 10 cm condition (1.89±0.56). The latter was significantly (*p*<0.05) lower than the SRRTb of the 15 cm condition (2.48±0.62). Illumination, barrier type, and barrier color, however, all had an insignificant effect on SRRTb.

Figure 5. here

Figure 6 shows the SRRTa results for the various experimental conditions. The SRRTa was significantly (*p*<0.0001) affected by barrier height. The SRRTa of the 5 cm condition (1.43±0.71) was significantly (*p*<0.05) lower than that of the 10 cm condition (2.05±0.74). The latter was significantly (*p*<0.05) lower than the SRRTa of the 15 cm condition (2.68±0.73). Illumination, barrier type, and barrier color, again however, all had an insignificant effect on SRRTa.

Figure 6. here

Figure 7 shows the GDR statistics under the various experimental conditions. The effect on GDR was significant (*p*<0.0001) in the case of barrier height. The GDR of the 5cm condition (1.76±0.76) was significantly (*p*<0.05) lower than that of the 10 cm condition (2.33±0.63). The latter was significantly (*p*<0.05) lower than the GDR of the 15 cm condition (2.89±0.66). The effects of illumination, type and color of barrier on GDR were all insignificant, however.

Figure 7. here

3.2 Foot Clearance

The behavior of the MFClead under the experimental conditions is shown in Figure 8. The ANOVA results show that the MFClead was significantly affected by the barrier type (*p*<0.01) and the illumination condition (*p*<0.0001). Posterior comparisons results indicate that the MFClead of the stick barrier (126.15±44.78 mm) was significantly (*p*<0.05) higher than that (115.84±32.70 mm) of the board barrier. The MFClead of the dimmed condition (128.85±40.90 mm) was significantly (*p*<0.05) higher than that (113.10±36.43 mm) of the normal illumination condition. But, both barrier height and barrier color had no significant effect on MFClead.

Figure 8. here

Figure 9 shows the MFClag statistics under the experimental conditions. The ANOVA results indicate that the MFClag was significantly affected by the barrier type (*p*<0.0001), illumination condition (*p*<0.001), barrier height (*p*<0.05) and barrier color (*p*<0.05). The MFClag for the stick barrier (132.12±47.24 mm) was significantly (*p*<0.05) higher than that (111.36±30.64 mm) for the board. The MFClag in the dimmed condition (127.72±42.53 mm) was significantly (*p*<0.05) higher than that (115.69±38.74 mm) for normal illumination. The MFClag for the dark gray barrier (125.45±41.43 mm) was significantly (*p*<0.05) higher than that (117.96±40.47 mm) for the white one. The MFClag for the 5 cm barrier height (127.52±42.59 mm) was significantly (*p*<0.05) higher than that (117.17±41.49 mm) for the 15 cm condition. The differences in the MFClag for the 10 cm condition (120.40±38.61 mm) with those for the other two barrier height conditions were both insignificant (see Table 1).

Figure 9. here

Table 1 here

3.3 Step length

Figure 10 shows the results for ST3 under the experimental conditions. The ANOVA results indicate that ST3 was significantly affected by the illumination condition (*p*<0.001) and barrier type (*p*<0.05). Duncan’s multiple range test results showed that ST3 in the normal illumination condition (733.33±54.69 mm) was significantly (*p*<0.05) longer than that (713.64±67.46 mm) under the dimmed condition. The ST3 in the board barrier condition (728.72±62.73 mm) was significantly (*p*<0.05) longer than that (718.22±61.20 mm) in the stick barrier condition. Both barrier height and barrier color had no significant effects on ST3.

Figure 10. here

The ANOVA results indicate that the illumination condition was significant for both ST1 (*p*<0.01) and ST5 (*p*<0.01). ST1 for the normal illumination condition (674.37±44.48 mm) was significantly (*p*<0.05) longer than that (660.36±66.26 mm) for the dimmed condition. ST5 for the normal illumination condition (669.31±49.70 mm) was also significantly (*p*<0.05) longer than that (658.15±49.13 mm) for the dimmed condition. The effects of barrier height, type, and color on both ST1 and ST5 were not significant (see Table 2).

Table 2 here

The ANOVA results indicate that none of the experimental factors had significant effect on either ST2 or ST4.

Table 3 shows the multiple comparison results for the step lengths before and after barrier crossing. ST3 was significantly (*p*<0.05) longer than all other lengths. ST2 was shorter (*p*<0.05) than ST1 and ST3.

Table 3 here

4. Discussion

Barrier height has long been considered an important factor affecting RT (Chen et al., 1991; Chou & Draganich, 1998; Garman et al., 2015; Kunimune and Okada, 2017; Li et al., 2019b). And, in this study, all RT measures, namely the SRRTb, SRRTa, and GDR, increased significantly (*p*<0.0001) as the barrier height increased, indicating that the higher the barrier, the greater the perceived RT and gait disturbance.

Poor illumination is another environmental cause of tripping and even falling (Huang et al., 2013). However, results of this study challenge that generalization. In the earlier study (Li et al., 2019b), approximately a third of the participants reported NO RISK and more than 50% of the participants reported LOW RISK before walking in the dimmed condition. Similar results were found in the current study. The participants made their SRRTb choices primarily on the basis of their visual inspection of the walkway in front of them. The SRRTa, on the other hand, was reached on the basis of the experience crossing the barrier. It is thus to be expected that illumination would be determinative of SRRT. But, the only significant factor affecting both the SRRTb and SRRTa in the current study was barrier height. Illumination, barrier type, and barrier color were all insignificant. This is inconsistent with the findings in the the earlier study (Li et al., 2019b), and is possibly attributable to the use of the motion tracking system in the current study. Each camera of this system featured a red LED light. The cameras worked by capturing the reflections of the LED lights on the markers. Even though the illuminance measured on the six spots on the walkway was very low (<0.01 lx), it was still much higher than that (2.7×10-3 lx) in the previous study (Li et al., 2019b). Therefore, our participants might have been able to see more than those in Li et al. (2019b) and vision-related factors such as color and type of barrier and illumination became insignificant in determination of the SRRT.

When moving over a barrier, the leading foot is in the front. The participants could see the movement of this foot, giving them better control of it crossing the barrier. As a result, there was almost no MFClead differences between the 5 cm, 10 cm, and 15 cm barrier height conditions. These results are consistent with those of Pan et al. (2016) and Kunimune and Okada (2017). The participants probably estimated the barrier height, and then controlled movement of their leading foot to give it the constant MFC (approximately 120 mm) required to guarantee safe crossing of the barrier. The lagging foot, on the other hand, is behind the body. The participants could not see this foot and hence were incapable of maintaining the same MFC over different barrier height conditions. This is a possible explanation of why the MFClag was significantly (*p*<0.05) affected by barrier height (see Table 1).

Both the MFClead and the MFClag were significantly (*p*<0.001) affected by the illumination condition. The MFClead and MFClag in the dimmed condition were significantly (15.75 mm and 12.03 mm) higher than in the normal condition, respectively. This finding is consistent with the studies of Rodrigues et al. (2009) and Kunimune & Okada (2017), the latter of which also found that vision conditions affected the MFC of both the leading and trailing foot. The participants presumably were raising their foot higher when the illumination conditions were poor so as to reduce the risk of tripping.

When crossing the barrier, the MFClead in the stick barrier condition was significantly (*p*<0.05) higher (10.31 mm higher) than that in the board barrier condition. And the MFClag in the stick condition was also significantly (*p*<0.05) higher than that in the board condition, up 20.76 mm. When the barrier was a stick, the participants tended to raise both of their leading and lagging feet higher upon crossing the barrier than when the barrier was a board. This finding that barrier type affects leg movements upon barrier crossing is consistent with that in the earlier study (Li et al., 2019b).

As for mean step length, ST3 (723.49±62.14 mm) was significantly (*p*<0.05) longer than ST2 (657.08±91.44 mm) and ST4 (663.76±60.66). ST 2 was significantly (*p*<0.05) shorter than ST1 (667.36±56.81). Similar results have also been reported by Berard & Vallis, 2006. This clearly indicates that the participants reduced their step length one step in front of the barrier as they prepared to pass it, before increasing their step length in the next step to guarantee safely crossing over it.

The mean ST3 in the dimmed condition (713.64±67.46 mm) was significantly (*p<*0.0001) shorter than that under normal lighting (733.33±54.69 mm). This result is also consistent with that of Berard and Vallis (2006). They found that participants generally decrease their step length when negotiating a barrier in poor lighting conditions. Short steps are a common gait strategy adopted when the risk of falling is great. ST1, the step length two steps before the participants crossed the barrier, was also significantly (*p*<0.01) shorter in the dimmed condition than in the normal lighting condition. This is consistent with the finding of Novak and Deshpande (2014) that vision conditions affect pre-barrier step length significantly and also with the notion that the trajectory of the lead foot is planned at least two steps before reaching the barrier (Timmis & Buckley, 2012). Our participants might also have started to adjust their gait two steps before crossing the barrier especially when the illumination was poor, as is suggested by our ST1 data for the dimmed condition.

ST3 was not affected by barrier height. This is consistent with findings in the literature (Chen et al., 1991; Pan et al., 2016). On the other hand, ST3 was significantly influenced by barrier type (*p<*0.05). ST3 in the stick condition (718.22±61.20 mm) was significantly (*p*<0.05) shorter than that in the board condition (728.72±62.73 mm). The participants adopted a conservative gait strategy by reducing their step length stepping over the stick barrier, a strategy that they did not feel was necessary when the barrier was a board. This phenomenon is consistent with the larger MFClead and MFClag values seen in the stick condition. Of the total 576 trials in our experiment, only 4 resulted in foot-barrier contacts. Three of those cases occurred in the stick condition. This implies that a stick on the walkway is more likely to lead to a trip than a board. The consistency with our MFClead and MFClag results and the consistency with the findings in the earlier study (Li et al., 2019b) suggest sticks are harder to negotiate than boards.

There were limitations to this study. First of all, we assumed that the friction of the shoe on the floor was not a significant factor affecting RT upon barrier crossing when the shoe-floor interface was slip-resistant. Our rubber-soled lab shoes were believed to be slip resistant on the walkway even though the friction coefficient between the shoe sole and floor was not measured. Future research may be needed to test more combinations of shoes and floor material. Secondly, only two types of barrier over three heights were tested. Many other types of barrier with different heights appear on walkways both at work and in public spaces. Our results cannot be generalized to explain RT and MFC phenomena beyond our experimental conditions. Studying the effects on the risk of tripping of barrier types and heights other than those adopted in the current study remain interesting topics for future research. Finally, we have tested only a young male sample. The effects of gender and age group on the SRRT and MFC could also be interesting research topics in the future.

5. Conclusions

Our hypotheses were partially supported. The MFC of the lagging foot was significantly affected by illumination condition and type, height, and color of barrier while the MFC of the leading foot was significantly affected only by illumination condition and barrier type. This implies that participants had better control of their leading foot than their lagging foot given the environmental conditions in our experiment. The step length upon barrier crossing was also significantly affected only by illumination condition and barrier type. This may suggest that the participants adjusted step length upon barrier crossing, regarding it as primary, in the case of changes in these two factors. The findings of this study enhance our understanding of human gait upon barrier crossing and will be beneficial for the prevention of tripping and falling.