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

**Abstract**

A study was designed to investigate the gait parameters upon crossing a barrier and the 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 and 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 barriers 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 significant (*p*<0.0001) higher GDR. The barrier type (*p*<0.01) and illumination conditions (*p*<0.001) were significant 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 mechanism when moving over barriers on walkways. They provide meaningful information 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 our society (Amandus et al., 2012; Ramaswamy & Mosher, 2018). The proportion of falls among all types of injury in the globe has increased from 23.1% in 1997-2007 to 27.7% in 2007-2017 (James et al., 2018). During 2009 to 2018, the proportions of falls at work in Taiwan and the United States were between 15.82% and 21.21%, and between 24.35% and 26.97% among all occupational injuries, respectively (BLS, 2019; OSHA, 2019). Falls occur because of slip, trip, loss of balance, and some 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 occurred because of tripping (Berg et al., 1997; Overstall et al., 1977). Thus, studying the mechanism and influencing factors of tripping are significant for the safety for both the public and the workers.

Previous studies have shown that the factors causing tripping can be divided into two aspects: unsafe environments and unsafe behaviors (Huang et al., 2013; OSHC, 2018). Poor lighting conditions and improper gait pattern when negotiating a barrier are examples of unsafe environment and behavior, 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 has a poor vision may not see floor condition clearly and hence has a higher probability been tripped. Patla and Greig (2006) found that the probability of tripping could be as high as 53% when walkers’ sight were blocked. Illumination condition is one of the environmental factors affecting vision and thus the risk of tripping. The literature has indicated that the risk of tripping in the dimmed environment was 15.5 times of that in the normal illumination condition (Li et al., 2019b). A pedestrian will not be able to visually spot a pavement barrier if the illumination is lower than a threshold value (Fotios and Uttley, 2018).

In addition to illumination condition, walking speed also has an influence on pedestrians' capability to avoid a barrier on the road. Pedestrians may not have enough time to adjust their gait when moving over a barrier due to a fast walking speed which 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 the increasing pace when moving over a barrier (Draganich & Kuo, 2004; Schulz, 2011).

Barrier on the ground is surely undesirable. Berard and Vallis (2006) requested their participants to walk with one or two barriers on the path. They measured the distance between the toe and the barrier when moving over the barrier(s) and found that this distance of the two-barrier condition was shorter than that of the one-barrier condition. Lowrey et al. (2007) measured the time of the participants moving across the barriers. Their results showed that the time to cross the second barrier when there were two barriers was longer than the time 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 barrier leads to high probability of tripping. Chou and Draganich (1997, 1998) explored the influences of barrier height on gait parameters of the trail foot when crossing barriers. 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 bodily functions could 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 had lower center of pressure of the stance foot and peak foot velocity when the toe was above barrier than the younger ones. Older adults, therefore, had higher probability of tripping 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 pattern on their lower limbs have more difficulty to cross barriers on the ground and thus are suffering higher risk of tripping.

Trip and fall may occur if a walker does not have sufficient foot clearance when moving over a barrier. One of the kinematics parameters 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). It 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 minimum space 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 were not only doubled by the presence of 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 was significantly affected by lighting condition and characteristics of barrier on a walkway such as type, height, and color. However, they did not examine the effects of lighting condition and characteristics of 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 were to test these hypotheses so as to increase the knowledge base of the mechanism of tripping accidents. The SRRT data and step length before and after crossing a barrier was also investigated to discussed the gait behaviors for barrier crossing.

2. Materials and Methods

We conducted a gait experiment in the 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, right of the participants were 0.78 (±0.41), 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. 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 in the literature (Li et al., 2019b).A walkway of 6 m long was prepared. The floor of this walkway was covered with dark gray ceramic tiles. Two types of barrier were prepared. 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 pieces of both the sticks and boards were prepared. One of them were dark gray which were the same color as the floor surface. The others were white. The stick and board of this color had a high contrast with the floor surface as compared to those of the gray stick and board.

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 were easy to move. The 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 conditions. The normal condition was when all the fluorescent lights in the laboratory were turned on. This condition is typical for office work in local institutions. The dimmed condition, on the other hand, was simulated when all the windows were blocked and all the lights were turned off except 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 were 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 on the gait of the participants upon barrier crossing using the scale: 1- no disturbance: walked smoothly, 2- slight disturbance: walked slow down slightly, 3- medium disturbance: walked slow down obviously, 4- serious disturbance: stop shortly before the barrier to adjust the gait, and 5- foot-barrier contact. Foot-barrier contact implies onset of a tripping.

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

The MFC values were calculated 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 were also calculated and was termed MFClag.

Figure 3. here

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 has 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 step 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 joined trials 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 deviation of all the variables were calculated. The Kruskal-Wallis test and Wilcoxon rank sum test were performed for all the SRRT and GDR data to examine the significance of the variables comprised the experimental condition. Analysis of variance (ANOVA) and Duncan’s multiple rang test were performed MFC and step length data. The SAS® 9.0 (SAS Institute Inc., Cary, NC) software was used for statistical analyses. A significance level of α=0.05 was adopted.

3. Results

3.1 Subjective Ratings

Figure 5 shows the SRRTb statistics under experimental conditions. The Kruskal-Wallis test results revealed 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). The illumination condition, barrier type, and barrier color were all insignificant on SRRTb.

Figure 5. here

Figure 6 shows the SRRTa results under 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 condition, barrier type, and barrier color were all insignificant on SRRTa.

Figure 6. here

Figure 7 shows the GDR statistics under experimental conditions. The effects of GDR were significant (*p*<0.0001) on 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 that 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.

Figure 7. here

3.2 Foot Clearance

Figures 8 shows the results of the MFClead under experimental conditions. The ANOVA results showed that the MFClead was significantly affected by the barrier type (*p*<0.01) and the illumination condition (*p*<0.0001). Posterior comparisons results showed 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. Both barrier height and barrier color had no significant effects on MFClead.

Figure 8. here

Figures 9 shows the MFClag statistics under experimental conditions. The ANOVA results indicated 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 of the stick barrier (132.12±47.24 mm) was significantly (*p*<0.05) higher than that (111.36±30.64 mm) of 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) in the normal condition. The MFClag of the dark barrier (125.45±41.43 mm) was significantly (*p*<0.05) higher than that (117.96±40.47 mm) of the white one. The MFClag of the 5 cm barrier height (127.52±42.59 mm) was significantly (*p*<0.05) higher than that (117.17±41.49 mm) of the 15 cm condition. The differences of the MFClag between the 10 cm condition (120.40±38.61 mm) and those of the other two barrier height conditions were both insignificant (see Table 1).

Figure 9. here

Table 1 here

3.3 Step length

Figures 10 shows the results of ST3 under experimental conditions. The ANOVA results indicated 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) higher than that (713.64±67.46 mm) of the dimmed condition. The ST3 in the board barrier condition (728.72±62.73 mm) was significantly (*p*<0.05) higher 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 indicated that illumination condition was significant on both the ST1 (*p*<0.01) and ST5 (*p*<0.01). ST1 in the normal illumination condition (674.37±44.48 mm) was significantly (*p*<0.05) higher than that (660.36±66.26 mm) in the dimmed condition. The ST5 in the normal illumination condition (669.31±49.70 mm) was significantly (*p*<0.05) higher than that (658.15±49.13 mm) in the dimmed condition. The effects of barrier height, type, and color on both ST1 and ST5 were not significant (see Table 2).

Table 2

The ANOVA results indicated that none of the experimental factors had significant effect on both the ST2 and ST4.

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

Table 3 here

4. Discussion

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

Poor illumination condition is one of the environmental causes of tripping and even falling (Huang et al., 2013). In one of the previous studies (Li et al., 2019b), approximately a third of the participants reported NO RISK before they walked in the dimmed condition and more than 50% of the participants reported LOW RISK. Similar results were found in the current study. The participants determined the SRRTb primarily based on their visual judgements. The SRRTa, on the other hand, was rated based on their experience of barrier crossing. 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 was inconsistent with the findings in the literature (Li et al., 2019b). The reason for this inconsistency might be attributed to the use of the motion tracking system in the current study. Each camera of this system was accompanied with a red LED light. The cameras captured the reflective light of these LEDs on the markers. Even though the illuminance 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 better visions than those in Li et al. (2019b) and vision-related factors such as color and type of barrier and illumination became insignificant on the SRRT.

When moving over a barrier, the leading foot was in the front. The participants could see the movement of this foot and could have better control of this foot to cross the barrier. There was almost no MFClead difference among the 5 cm, 10 cm, and 15 cm barrier height conditions. These results were consistent with those in Pan et al. (2016) and Kunimune and Okada (2017). The participants probably estimated the barrier height, and then controlled their leading foot to have a constant MFC (approximately 120 mm) which would guarantee safety crossing over the barrier. The lagging foot, on the other hand, was behind the body. The participants could not see this foot and hence was incapable to maintain the same MFC over different barrier height conditions. This could explain 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 higher than those in the normal condition by 15.75 mm and 12.03 mm, respectively. This finding was consistent with those in the previous studies (Kunimune & Okada, 2017; Rodrigues et al., 2009). Kunimune and Okada (2017) found that vision condition affected the MFC of both the leading and trailing foot. The participants tended to raise their foot higher when the illumination condition was poor so as to reduce the probability of tripping.

When crossing the barrier, the MFClead in the stick condition were significantly (*p*<0.05) higher than that in the board barrier condition by 10.31 mm, and the MFClag in the stick barrier condition were significantly (*p*<0.05) higher than that in the board condition by 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 implies that barrier type could affect the leg movements upon barrier crossing was consistent with that in the literature (Li et al., 2019b).

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 those of ST1 (667.36±56.81). Similar results have also been reported (Berard & Vallis, 2006). This clearly indicated that the participants reduced their step length one step in front of the barrier for preparation to pass the barrier. They increased the step length in the next step to guarantee safe crossing of the barrier.

The ST3 in the dimmed condition (713.64±67.46 mm) was significantly (*p<*0.0001) shorter than that in the normal lighting condition (733.33±54.69 mm). This result was consistent with that in Berard and Vallis (2006). They found that participants generally decrease their step length when moving across the barrier in poor lighting condition. Such a gait is one of the common gait strategies for safe walking. ST1 was the step lengths two steps before the participants crossed the barrier. This step length in the dimmed condition was significantly (*p*<0.01) shorter than that in the normal lighting condition. This was consistent with those in Novak and Deshpande (2014) where they found vision condition affected the pre-barrier step length significantly. The trajectory of the lead foot was planned at least two steps before reaching the barrier (Timmis & Buckley, 2012). Our participants might also start to adjust their gait two steps before crossing the barrier especially when the illumination was poor. This was confirmed by our ST1 data especially in the dimmed condition.

ST3 was not affected by the barrier height. This was consistent with the findings in the literature (Chen et al., 1991; Pan et al., 2016). On the other hand, ST3 was significantly influenced by the barrier type (*p<*0.05). The 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 conservative gait strategies by reducing their step length upon barrier crossing when they encountered stick barrier than when the barrier was a board. Such a phenomenon was consistent to our outcomes in both MFClead and MFClag. There were a total of 576 trials in our experiment. Only 4 foot-barrier contacts occurred. Three of these cases occurred in the stick condition. These implies that a stick on the walkway was more likely to lead to a trip than a board. This was consistent with our results of MFClead and MFClag, and was also consistent with the findings in the literature (Li et al., 2019b).

This were limitations of this study. First of all, we assumed that the friction of the floor was not a significant factor affecting the 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 barriers under three heights were tested. Many other types of barrier with different heights could appear on the walkways both at work and in the public sector. Our results cannot be generalized in explaining the RT and MFC phenomena beyond our experimental conditions. Studying the effects of barrier types and heights, other than those adopted in the current study, on the risk of tripping may be interesting topic in the future. Finally, we have tested only a young male sample. The effects of gender and age group of human participants 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 considering 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 imply that the participants adjusted the step length upon barrier crossing primary because they found changes of those two factors. The findings of this study enhance our understanding of human gait upon barrier crossing which will be beneficial for the prevention of tripping and falling.