FOOT PLACEMENT IN OBLIQUE STAIR DESCENT

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Extensive research has been conducted on stair safety as a loss of balance due to a misplaced step on a stair can result in a fall and serious injury. One aspect of stair safety that has not been well studied is oblique (angled) stair descent/ascent. Since oblique stair geometry affects the distance travelled and the theoretical symmetry of one's stance, there are potential implications for fall risk. The purpose of this study was to investigate whether there are adaptations in foot placement that pedestrians demonstrate when descending stairs at oblique angles. Sixteen participants descended steps along two paths – 0 and 45 degrees. Kinematic data of the lower limbs were collected to calculate average step length, average step width, and toe placement. The data suggest that pedestrians compensate for angled descent by narrowing their step width and using a biased foot placement relative to the step edges, such that the inside foot (the foot furthest from the flared side) lands further forward on the step than the outside foot (the foot closest to the flared side). These variations from straight stair descent provide a more symmetric stance for oblique stair descent and may reflect adaptations to reduce the risk of a misstep.

INTRODUCTION

There are a wide variety of common staircase configurations, including straight staircases, multiple flight 'dogleg' staircases, winding 'helical' staircases, and composite staircases with flared (i.e. oblique) sides. In urban centers in particular, exterior staircases with oblique sides are often found at the entrances of buildings (Figure 1). Foot placement on stairs is important as a loss of balance due to a misplaced step can result in serious injury if it leads to a fall (Cohen, 1985).

Approximately two million people sustain stair related disabling injuries yearly in the U.S. (Young, 1996) and 92% of occupational stair accidents happen when descending stairs (Cohen, 1985). In the past, human error and stair design have traditionally shared the blame for these accidents. The ergonomics approach to stair accident prevention as an environmental intervention is gaining popularity since building design has a more pronounced contribution than previously assumed (Pauls, 1985). Public knowledge of the stair-accident relationship is also thought to be a cause for increased litigation surrounding accidents on stairs (Pauls, 1985). The impact of these injury statistics and legal implications has fuelled research analyzing optimal construction materials, tread depth, riser height, railing characteristics and subjective experience in order to improve stair safety (Cohen, 1985; David, 1992; Fitch, 1974; Pauls, 1982; Pauls, 1985; Young, 1996).

Safe stair use requires reachable and graspable handrails, good visibility, and stair treads (the space available for pedestrians to place their foot) that are long enough to ensure secure footing (Pauls, 1982; Pauls, 1985; Toowoomba, 1985). Riser height is also a critical factor for safe stair use. Appropriate riser height and tread depth are both necessary as there is a significantly increased number of incidents on stairs as rise height increases and run or tread depth decrease (Pauls, 1985; Templer, 1983; Toowoomba, 1985). Retaining adequate tread depth is necessary because slips dues to overstepping are the most frequent type of slips that result in injury on stairs, due to the danger of the continued forward trajectory (Pauls, 1985; Young, 1996).

Furthermore, the riser heights and tread depths must remain consistent throughout a flight of stairs. Uniformity of step-to-step geometry is a fundamental principle of safe stair design (Templer, 1992; Woodson, 1992), as has been reflected in building codes for decades (see New York State Building Code, 2006; California State Building Code, 2007; Ontario Building Code, 1990 to 2006; and National Building Code of Canada, 1985 for examples).

Despite the extensive amount of research conducted for straight stairs concerning step height, step length, handrail design, and safety standards (David, 1992), there is no available research regarding oblique descent/ascent on stairs and the potential effect of oblique descent/ascent on pedestrian safety. During oblique stair descent, the angled path of travel relative to the steps results in a longer tread depth, leaving more room for foot placement.

The angled route also results in an interesting geometric anomaly that does not apply to straight stair descent. During oblique descent, maintaining a consistent foot placement relative to the edge of the steps theoretically results in a non-symmetric alternating stance, as shown in Figure 2. Nevertheless, common experience demonstrates that pedestrians routinely descend these flared stairs at an angle without incident. Some gait asymmetries are normal during level walking (Sadeghi, 2000). There is little support, however, that these inherent asymmetries during straight, level walking are functional (Seeley, 2008). However, when turning 90 degrees, stride length decreases asymmetrically (Strike, 2009). Thus, any asymmetries in oblique stair descent that differ significantly from straight down descent would be compensatory due to the angled route.

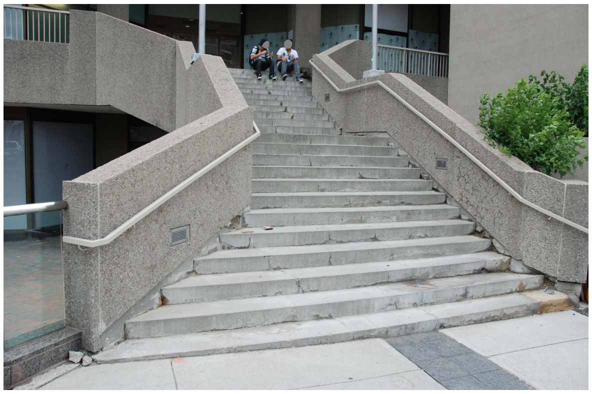

Figure 1: Site examination photograph of an exterior staircase with flared sides in an urban center.

This project aimed to study foot placement and gait adaptations of pedestrian test subjects as they descended stairs along an oblique path compared to a straight path. The purpose of the study was to investigate whether there are any adaptations in foot placement or gait adaptations that pedestrians demonstrate when descending stairs at oblique angles. To our knowledge, no such study has been previously published.

Based on the geometry of oblique stair descent, it was hypothesized that pedestrians may use one or both of the following adaptation strategies to allow them to descend stairs obliquely with a more symmetric alternating stance:

1. A more narrowed step width. This potential adaptation strategy would help to even out the length of the alternating stances, as shown in Figure 3.
2. A non-constant foot placement relative to the stair nosing (i.e. edge), with the foot closest to the flared side during descent (referred to as the 'outside foot' in this study) being placed further back from the stair nosing than the foot furthest from the flared side (referred to as the 'inside foot'). This potential adaptation strategy would also help to even out the length of the alternating stances.

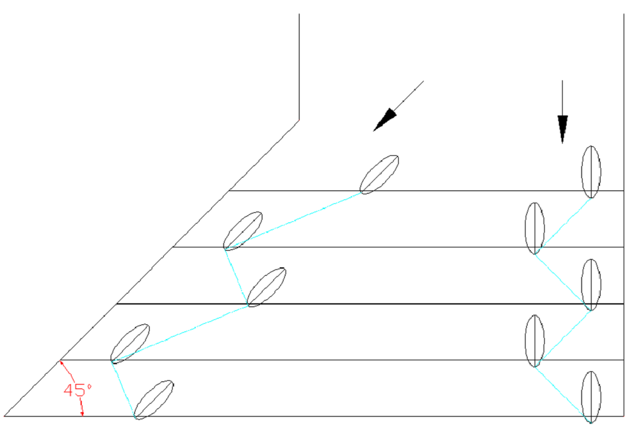

Figure 2: Illustration of the theoretical geometry of oblique vs. straight stair descent/ascent. Note the non-symmetric alternating stance along the oblique path if foot placement relative to the step edge is kept constant.

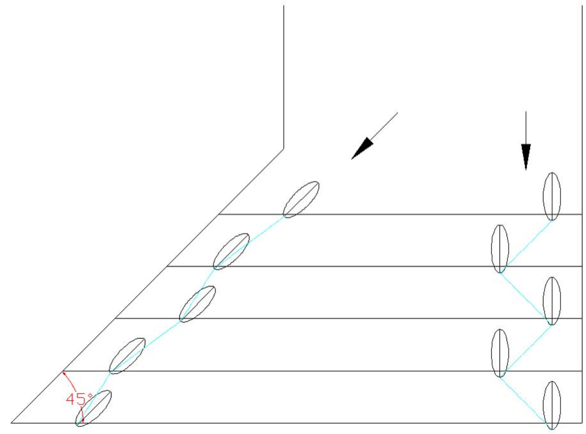

Figure 3: Predicted effect of narrowing one's step width during oblique stair descent. Note the near-symmetric alternating stance as compared to Figure 2 above.

METHODS

Sixteen participants (8 male, 8 female) from the university student population participated in this study (Table 1). Participants were excluded if they had a history of low back, knee, or leg pain or if they experienced a balance or gait condition in the past 12 months. This study was reviewed by the Office of Research Ethics at the University of Waterloo, which granted ethics clearance.

Table 1. Participant Anthropometrics; mean and (SD)

Gender	Age (yr)	Height (m)	Mass (kg)
Female	21.6 (1.2)	1.6 (0.1)	62.3 (8.0)
Male	23.3 (2.5)	1.8 (0.09)	84.0 (13.1)

Participants were instrumented with iRED markers for collection of kinematic data with an Optotrak Certus motion capture system (Northern Digital Inc., Waterloo, ON, Canada). Markers were placed over the following anatomical landmarks: first and fifth metatarsal heads; dorsum of foot, lateral aspect of heel. The following anatomical landmarks were digitized in a standing reference pose: medial and lateral malleoli; medial and lateral knee joint line; greater trochanter; anterior aspect of iliac crest. Rigid bodies, consisting of 4 markers each, were fixed to the lateral aspect of the shank; thigh and on rigid fins affixed to the sacrum.

A 10 second calibration trial was collected with the participant standing quietly to define anatomical coordinate systems for each segment. Kinematic data were collected at a sample rate of 32Hz.

In the various trials, participants were instructed to walk straight down or obliquely down custom-built stairs, which were widened obliquely at a 45° angle on the right side when descending (Figure 4). Hence, in this study the 'outside foot' was the right foot and the 'inside foot' was the left foot. The order of direction of descent was block randomized for each participant.

The staircase consisted of three stairs with rise of 20 cm, run of 30 cm, and no nosing protrusions. Vinyl tile was used to cover the stairs in attempt to make them appear more like the surrounding floor and to avoid visual distraction. A vertical pole, placed as a target along the desired path, guided the two routes down the stairs. Participants began each descent with the foot of their choice and descended at a speed of their choice, with the constraint of only placing one foot on each step. This sequence was completed until five successful trials in each direction of descent were attained.

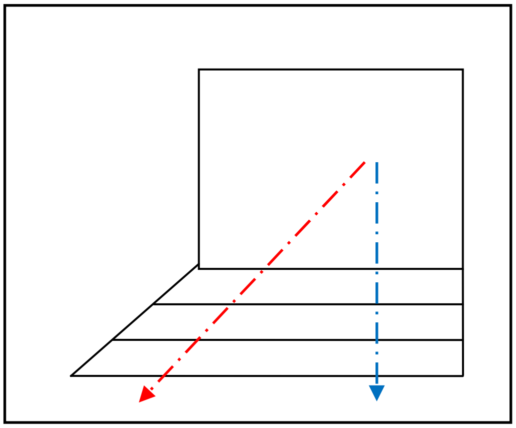

Figure 4: Diagram of the test apparatus stairs and the direction of descent for the trials.

Kinematic data was processed using Visual 3D (C-Motion Inc., Germantown, MD, USA). Average step width, step length and toe placement relative to the step edge for each foot were calculated for the 0° and 45° conditions. Step length was defined as the anterior-posterior toe-toe distance between feet. Step width was defined as the medial-lateral distance between toes of the feet. Toe placement was defined as the distance that the toe was placed past (i.e. over) the edge of each step. Toe placements that were prior to the edge of the step were measured and recorded as negative distances.

A one-way, repeated measures ANOVA was used to identify any differences in step width and step length for each condition. A two-way, repeated measures ANOVA with factors of descent path and foot (inside vs. outside) was used to identify any differences for toe placement. Statistical tests were calculated using SAS Statistical Software (v.9.1, SAS Institute Inc, Cary, NC, USA) and significance was accepted at the $p<0.05$ level.

RESULTS

Table 2 summarizes the results of the study, including average step width, step length and toe placement for the 0° and 45° descent paths.

Step width and step length were significantly different for the two descent conditions, with step width decreasing significantly and step length increasing significantly for a 45 degree descent path compared to the straight condition ($p<0.05$).

For oblique descent, the toe of the inside (left) foot was significantly more forward on the step than the toe of the outside (right) foot ($p<0.05$). On average, the left toe was placed 2.9 cm over the step edge, whereas the right toe was placed 0.4 cm behind the step edge.

Toe placement relative to the step edge was also significantly different for the two descent conditions, with more of the foot off the stair (i.e. past the stair nosing) during straight descent ($p<0.05$).

Table 2: Step width, length and toe placement results; mean and (SD)

Path (°)	Step Width (cm)	Step Length (cm)	Toe Placement (cm)	
			Inside Foot	Outside Foot
0	**16.4 (3.0)**	**31.8 (2.0)**	**4.9 (5.6)**	**5.6(2.0)**
45	**9.5 (4.2)**	**42.8 (5.2)**	**2.9 (2.2)**	**-0.4 (2.4)**

DISCUSSION

The data suggest that participants adapted to angled geometry of stair descent by lengthening their step, narrowing their step width, placing their inside foot further forward on the stair than the outside foot, and keeping a greater proportion of both feet on the stair tread compared to straight descent.

The lengthening of steps during oblique descent of stairs is a necessary consequence of a longer path of travel from step to step when descending at an angle. The other two variations from straight stair descent (narrowing of step width and left-right differences in foot placement relative to the step edge) reflect an adaptation in foot placement that provides a more symmetric alternating stance when descending stairs at an angle. During the oblique descent trials, all test subjects placed the inside foot further forward on the stair than the outside foot.

Since the asymmetries seen in angled stair descent differ significantly from straight down descent, and since there is little support for another function for these asymmetries, it is reasonable to believe that the changes during oblique stair descent are indeed compensatory adaptations, as hypothesized. These adaptations may be linked to either maintaining a natural gait pattern or aimed at reducing the risk of a misstep when descending stairs at an angle. Additional analyses of heel and toe clearances are needed in this regard. Further research could also be conducted to study the development of these adaptations in pedestrians of various ages.

The data also demonstrated that for both feet in general, foot placement was more fully on the step tread surface during oblique descent than during straight descent. This finding may simply reflect the fact that increased tread surface is available for foot placement when descending steps at an angle (e.g. for a 30 cm tread depth step, the 'effective' tread depth available for foot placement if descending at a 45 degree angle is approximately 42 cm).

In general, an increase in effective tread depth would have a positive effect on pedestrian safety, up to a point. For straight stair descent, as tread depths increase above 14" (35.6 cm), the frequency of stair accidents starts to increase because pedestrians may be forced to adopt an uncomfortable or unnatural gait pattern such as an overly long stride (Jackson and Cohen, 1995; Cohen et al., 2009).

Aside from the adaptations observed in this study, it is conceivable that there are other adaptations in stair descent gait that assist pedestrians in negotiating stairs with oblique angles. Regardless, it appears from the findings that pedestrians are able to descend stairs at an oblique angle using a modified descent gait that helps avoid a theoretical asymmetry in stance. Additional research regarding speed of descent, gait patterns, muscle activation, and stair ascent are recommended. Other aspects to be included in future studies of oblique stairs could include, the influence of shoe length, and left vs. right foot dominance.

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