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Effect of cane length and swing arc width on drop-off and obstacle detection with the long cane

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Abstract

A repeated-measures design with block randomization was used for the study, in which 15 adults with visual impairments attempted to detect the drop-offs and obstacles with the canes of different lengths, swinging the cane in different widths (narrow vs wide). Participants detected the drop-offs significantly more reliably with the standard-length cane ($79.5\% \pm 6.5\%$ of the time) than with the extended-length cane ($67.6\% \pm 9.1\%$), $p < .001$. The drop-off detection threshold of the standard-length cane (4.1 ± 1.1 cm) was also significantly smaller than that of the extended-length cane (6.5 ± 1.8 cm), $p < .001$. In addition, participants detected drop-offs at a significantly higher percentage when they swung the cane approximately 3 cm beyond the widest part of the body ($78.6\% \pm 7.6\%$) than when they swung it substantially wider (30 cm; $68.5\% \pm 8.3\%$), $p < .001$. In contrast, neither cane length ($p = .074$) nor cane swing arc width ($p = .185$) had a significant effect on obstacle detection performance. The findings of the study may help orientation and mobility specialists recommend appropriate cane length and cane swing arc width to visually impaired cane users.

Keywords

Cane biomechanics; cane ergonomics; cane length; cane swing arc; cane technique; drop-off detection; long cane; obstacle detection; orientation and mobility; visually impaired; white cane

Introduction

Modern long cane design and techniques have changed little since their development in the 1940s. A long cane is constructed with a grip (rubber, foam, or plastic materials), a shaft (typically aluminum, graphite or fiberglass), and a tip (often made of plastic or other materials; LaGrow & Long, 2011). The length of the shaft generally ranges from 115 to 165 cm. The two-point touch technique – swinging the cane side to side, tapping either side in an arc slightly wider than the widest part of the body – and the constant contact technique – sweeping the cane from side to side in an arc slightly wider than the widest part of the body while keeping the cane tip in contact with the surface at all times – are the two cane

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techniques most widely used by travelers who are blind (LaGrow & Long, 2011). Regardless of which technique is used, detection of drop-offs and obstacles, a key component of preview offered by a long cane (Blasch, LaGrow, & De l'Aune, 1996), is crucial for the safety of blind travelers. Missing drop-offs such as descending stairs or curbs may cause a cane user to fall or stumble into the path of approaching vehicles. Missing obstacles such as construction cones or toys left on the sidewalk may also trip the cane user, resulting in falls and consequent fall-induced injuries.

Several recent studies have examined how different biomechanical factors affect drop-off detection with the long cane. How high the cane user lifts the cane tip when using the two-point touch technique was related to the ability to preview the walking surface for possible drop-offs (Bongers, Schellingerhout, van Grinsven, & Smitsman, 2002). Similarly, the constant contact technique was significantly better than the two-point touch technique for detecting drop-offs (D. Kim, Wall Emerson, & Curtis, 2009), particularly for inexperienced cane users (D. Kim, Wall Emerson, & Curtis, 2010b).

As for the effects of ergonomic factors on drop-off detection performance, no significant difference in drop-off detection performance was found between the nylon tips of different shapes (pencil, marshmallow, and curved; LaGrow, Kjeldstad, & Lewandowski, 1988). Similarly, no significant difference in performance was found between a regular marshmallow tip and a roller marshmallow tip with built-in bearings that allow the tip to rotate on the surface when the cane is swept from side to side (D. Kim, Wall Emerson, & Curtis, 2010a). However, a heavier cane was more advantageous than a lighter cane for detecting drop-offs when the constant contact technique was used, while there was no significant difference between a heavier cane and a lighter cane when the two-point touch technique was used (D. Kim, Wall Emerson, Naghshineh, & Auer, 2016).

With respect to the effects of biomechanical factors on obstacle detection performance, it was documented that pivoting the wrist when swinging the cane resulted in better body coverage than moving the whole arm (Wall & Ashmead, 2002). More recently, it was reported that the constant contact technique was better than the two-point touch technique for detecting shorter obstacles, but there was no significant difference in obstacle detection performance between the two techniques for taller obstacles (D. Kim & Wall Emerson, 2014).

Several studies investigated the effects of ergonomic factors on obstacle detection. It was reported that a cane with a shaft bent on the cane tip end to increase the contact area with the walking surface resulted in higher percentage of obstacle detection (Schellingerhout, Bongers, van Grinsven, Smitsman, & van Galen, 2001). It was also documented that the longer the cane, the better the body coverage (Bongers et al., 2002). In addition, several researchers in computer science and engineering disciplines tested the effectiveness of prototype electronic canes or wearable devices for detecting obstacles. Most of the tested devices have been designed to be used as a secondary device, complementing a traditional long cane as an attachment to the long cane (Gallo et al., 2010; S. Kim & Cho, 2013; O'Brien, Mohtar, Diment, & Reynolds, 2014; Pyun, Kim, Wespe, Schneller, & Gassert, 2013; Tahat, 2009; Wang & Kuchenbecher, 2012). The majority of these studies reported a

moderate improvement in object detection rate, largely as a result of detecting above-waist-level overhanging obstacles, which the traditional long cane is inherently unable to detect. However, many of the studies also reported an increase in time to complete a given route, likely due to the extra time required to process additional auditory and/or vibro-tactile feedback from the attached device. Although a few stand-alone electronic devices designed for replacing a long cane have also been tested (Bhatlawande, Mahadevappa, et al., 2014; Bhatlawande, Sunkari, et al., 2014; Bouhamed, Kallel, & Masmoudi, 2013; Jeslin, Vaishnavi, & Nivedha, 2015), none of these devices demonstrated the ability to reliably detect even large drop-offs. With little or no ability to detect drop-offs, missing which will likely cause falls (e.g. falling down stairs), these reported stand-alone devices, in their current form, appear to have limited practical implications for improving the safety of cane users.

The length of a long cane appears to affect how well the cane user can detect drop-offs and obstacles. A cane that comes up to 5 cm above the xiphoid process when placed vertically on the walking surface (standard length) was better at detecting drop-offs than the longer or shorter canes when the participants used the two-point touch technique (Wall & Ashmead, 2002). However, no significant difference in drop-off detection was found between the standard-length cane and the one that is 25 cm longer when the participants used the constant contact technique (D. Kim & Wall Emerson, 2012). As for obstacle detection, a significant positive correlation between cane length and object coverage rate ($r = .460$) was reported (Bongers et al., 2002). It was also documented that the individuals whose cane-holding-hand position is lower detected obstacles at a higher percentage than those whose cane-holding-hand position was higher (LaGrow, Blasch, & De l'Aune, 1997).

How wide an individual swings the cane side to side (cane arc width) also appears to have an effect on obstacle and drop-off detection. According to the standard cane technique prescribed in orientation and mobility textbooks, a cane user should swing the cane an inch wider than the widest part of the body on either side (LaGrow & Long, 2011). However, many cane users swing their cane much wider, stating such wider arc seems to better protect them from accidentally colliding with obstacles (P. Smith, 7 November 2015, personal communication; N. Stanford, 24 July 2015, personal communication). Results of studies on this topic are mixed. A study by Wall and Ashmead (2002) indicated that the wider the cane arc, the better the path coverage, while Bongers et al. (2002) reported that cane arc width correlates negatively with object coverage rate ($r = -.329$). In addition, some orientation and mobility specialists indicated that a cane arc prescribed by the standard cane technique (compared to much wider cane arc) allows cane users to detect drop-offs more reliably (S. Williams-Riseng, 9 June 2015, personal communication; R. Savage, 2 April 2015, personal communication).

One of the primary aims of this study was to determine whether a longer cane is more advantageous than a shorter cane for detecting obstacles but less advantageous for detecting drop-offs. Another primary aim of this study was to determine whether a standard cane arc is better than a wider cane arc for detecting both drop-offs and obstacles. As a secondary research question, this study also investigated the interactions between drop-off depth (or

obstacle's lateral position) and the independent variables included in the primary research aims.

Experiment 1 (drop-off detection)

Methods

Study design and participants—A repeated-measures design with block randomization was used for the study. We recruited 15 individuals who are legally blind and have no other disabilities, 14 of which completed the study. A summary of the participants' demographic information is shown in Table 1. Five participants stated that they travel independently almost every day, six reported that they travel independently 3–6 days/week, and three indicated that they travel independently <3 days/week.

Apparatus—Two prototype canes were built for the study (see Figure 1). The extended-length cane (162 cm long) was built with a pultruded carbon shaft (Goodwinds LLC), a nylon cylindrical tip (Ambutech MT3050 Slip-on Pencil Tip) weighing 10 g, and a foam golf grip that is 25.4 cm in length and 17 g in weight (Toski Ultralight Putter Grip). Pultruded carbon is a carbon-fiber-based material, manufactured by pulling fibers first through a bath of thermosetting resin and then a heated die, which gives it high rigidity for a low linear density (0.6 g/cm). The standard-length cane (122 cm long) was built with the same grip and tip, but a poplar rod was used as the shaft of the cane. Poplar is a common wood with a low linear density and good flexibility. In the Noise and Vibrations Laboratory at Western Michigan University (WMU), rigidity of each shaft was calculated by measuring the deflection produced by an applied force (see D. Kim, Wall Emerson, Naghshineh, & Auer, 2017, for details on the equipment setup and how shaft rigidity was measured). We used the cane shaft materials of different inherent rigidity in order to produce two prototype canes that are different in length but similar in rigidity and weight. The shaft for the extended-length cane was 92 g and has the rigidity of 83.3 N/m, while the shaft of the standard-length cane was 85 g and has the rigidity of 74.4 N/m.

A 9.8-m-long and 2.4-m-wide walkway formed with eight-carpeted plywood platforms (2.4 m long, 1.2 m wide, and 20.3 cm high) was used for the study (see Figure 2). We placed two plywood boards (0.9 m long and 1.2 m wide) laid on top of braced rectangular frames (0.9 m long, 1.2 m wide, and 5.1 cm high) against the lengthwise end of the walkway to vary the drop-off depth from trial to trial. The carpeting on the plywood boards was identical to that on the walkway, which was a measure aimed at preventing the participants from using tactile and/or auditory cues for drop-off detection (see D. Kim et al., 2009, for further details of the study apparatus and procedure).

Research procedure—Upon arriving at the study site, each participant signed the informed consent form approved by WMU's Human Subjects Institutional Review Board. Sleep shades (except for those with no vision at all such as those with a set of prosthetic eyes) and a full-size headphone set (Sony wireless stereo headset MDR-ZX770BT) connected to an MP3 player (Apple iPod 5th Generation) were worn by all participants during all trials. Each participant was positioned at the center of the walkway and aligned parallel to the walkway. To prevent participants from anticipating a drop-off at a predictable

distance, the distance between the participant and the drop-off was randomly varied from 4.3 to 9.1 m. At a signal from the experimenter, the participant approached the drop-off with either a standard-length cane or an extended-length cane. Standard-length cane (122 cm) comes up to approximately 5 cm above the xiphoid process when placed vertically in front of the body of an individual who is 169 cm tall (mean height for US adults); this is a standard method used for initial sizing of a long cane for an individual who needs a cane (LaGrow & Long, 2011). Extended-length cane (162 cm) comes up to approximately the eyebrow of an individual who is 169 cm tall when held vertically in front of the body; some cane users advocate for canes that come up to their eyebrows (Bickford, 1996).

Each participant was instructed to swing the cane slightly (approximately 3 cm) beyond the widest part of the body in the “narrow cane arc” condition while about 30 cm wider than the widest part of her body on each side in the “wide cane arc” condition. Upon detecting the drop-off, the participant stopped immediately and said “drop-off.” Upon completion of each trial, the experimenter guided the participant to the next starting point. Research assistants changed the depth of the drop-off for the next trial following a randomized schedule. When a participant failed to detect the drop-off, the experimenter, if needed, intervened to keep the participant from tumbling off the drop-off in a similar manner as is used when teaching mobility skills.

Participants practiced swinging the cane as specified by the conditions (i.e. narrow cane arc vs wide cane arc) in the hallway until they demonstrated the ability to reliably swing the cane as prescribed, which typically took 5–15 min. Upon completion of practice trials (two per condition), each participant completed four trials for each drop-off depth (2.5, 7.6, 12.7, and 17.8 cm) for the following four conditions: (1) standard-length cane with narrow cane arc, (2) standard-length cane with wide cane arc, (3) extended-length cane with narrow cane arc, and (4) extended-length cane with wide cane arc. That is, each participant completed a total of 64 trials. We also used a Latin square design to control for possible order effects. We recorded a trial as a miss if the participant fell off the drop-off or would have fallen off the drop-off had it not been for the experimenter’s intervention. In other words, a trial was recorded as either a “miss” or “detected.” Two independent raters scored the trials; interrater reliability was 96%.

Variables and analyses—Absolute drop-off detection threshold (50%) and drop-off detection rates were used as the measures of drop-off detection performance (dependent variables). We calculated the 50% absolute drop-off detection threshold for each of the four conditions stated above using a psychometric function outlined in Gescheider (1997). Drop-off detection rates were computed by dividing the total number of detections by total number of trials for each drop-off depth.

Cane length, which is a within-group variable with two categories (standard-length and extended-length), and cane swing arc width, which is also a within-group variable with two categories (narrow and wide), were the primary independent variables of the study.

Upon completion of descriptive statistical procedures, we used a two-way repeated-measures analysis of variance (ANOVA) to answer our primary research questions. As a secondary

analysis, we used a three-way repeated-measures ANOVA to examine possible interactions between drop-off depth and the above-mentioned independent variables. We used a significance level of .05 for all statistical tests (two tailed). The statistical power of the F -tests was .78 or higher when a large effect size ($f = .4$ or $r = .5$) was assumed (Cohen, 1988; Erdfelder, Faul, & Buchner, 1996; Field, 2009). All statistical analyses, except for power analyses (G*Power version 3.1.9.2: <http://www.gpower.hhu.de/en.html>), were conducted with SPSS version 22 (SPSS, Inc., Chicago, IL).

Results

Main effects—The three-way interaction among cane length, cane arc width, and drop-off depth was not statistically significant, $F(2.11, 27.47) = 3.41, p = .055$. No statistically significant two-way interaction between cane length and cane arc width was observed, either, $F(1, 13) = 3.21, p = .097$; therefore, the main effects of these two variables were examined (Keppel, 1991). The drop-off detection threshold for the standard-length cane (4.1 ± 1.1 cm) was statistically significantly smaller than that for the extended-length cane (6.5 ± 1.8 cm), $F(1, 13) = 46.02, p < .001, r = .88$. Similarly, the overall drop-off detection rate for the standard-length cane ($79.5\% \pm 6.5\%$) was statistically significantly higher than that for the extended-length cane ($67.6\% \pm 9.1\%$), $F(1, 13) = 40.53, p < .001, r = .87$. In addition, drop-off detection threshold for the condition in which the participants swung the cane in a narrow arc (4.3 ± 1.4 cm) was statistically significantly smaller than that in which the participants swung the cane in a wide arc (6.4 ± 1.6 cm), $F(1, 13) = 28.24, p < .001, r = .83$. Similarly, the overall drop-off detection rate for the narrow arc condition ($78.6\% \pm 7.6\%$) was statistically significantly higher than that for the wide arc condition ($68.5\% \pm 8.3\%$), $F(1, 13) = 27.51, p < .001, r = .82$ (Table 2).

Interaction effects—We found a statistically significant interaction between cane arc width and drop-off depth, $F(1.61, 20.98) = 7.156, p = .001$ (see Figure 3). The advantage of swinging the cane narrowly over swinging it wide decreased as the drop-off depth increased. In fact, the detection rate for the largest drop-offs (17.8 cm) was identical (100% detection) for the narrow and wide cane arc conditions.

We also found a statistically significant interaction between cane length and drop-off depth, $F(1.40, 18.23) = 3.21, p < .001$ (see Figure 4). The advantage of the standard-length cane over the extended-length cane was largest for the 7.6-cm drop-offs (29.5%), while the largest drop-offs (17.8 cm) were detected 100% of the time regardless of the cane length.

Experiment 2 (obstacle detection)

Methods

Study design and participants—A repeated-measures design with block randomization was used for the study. In total, 15 individuals who are legally blind and have no other disabilities participated in the study. A summary of participant characteristics is shown in Table 3. In total, eight participants reported that they travel independently almost every day, four stated that they travel independently 3–6 days/week, and three stated that they travel independently <3 days/week.

Apparatus—We used the same prototype canes that we used in Experiment 1. We previously created cylindrical objects of different sizes (diameters of 5.1, 15.2, 25.4, and 35.6 cm) and heights (2.5, 7.6, 12.7, and 17.8 cm) with styrofoam and linoleum for a related study (D. Kim & Wall Emerson, 2014). Among these objects, using a conservative approach, we only used the 17.8-cm-high obstacles in this study in light of the fact that they pose the greatest risk of tripping the cane user, if missed (see Figure 5). These objects were presented on a participant's walking path either at the midline of the path or slightly off to the side (approximately 15 cm off either to the left or right from the midline) following a randomized schedule. The lateral distance from the midline to the off-center objects (15 cm) was determined to ensure that the participants consistently contact the objects with a part of their body (i.e. foot), rendering them tripping hazards, in the event they miss the objects with the cane. A 6.1-m-long rail (91 cm high), built with polyvinyl chloride (PVC) pipes, was placed beside the walking path for participants to trail with the free hand, allowing participants to walk consistently along the midline of the intended walking path (see Figure 6). This is a measure designed to ensure that the participant encounter the obstacle at the intended relative position from the sagittal plane of the body (see D. Kim & Wall Emerson, 2014, for further details of the study apparatus and procedure).

Research procedure—Sleep shades and a full-size headphone set connected to an MP3 player (as described in Experiment 1) were worn by all participants during all trials. Each participant was positioned at the midline of the obstacle detection walking path and properly aligned with the path before the beginning of each trial. To prevent participants from anticipating the obstacle at a predictable distance, the distance between the participant and the obstacle was randomly varied from 3 to 6 m. At a signal from the experimenter, the participant approached the obstacle on the indicated walking path with either the standard-length cane or the extended-length cane. Each participant was instructed to swing the cane about 3 cm beyond the widest part of the body in some conditions and about 30 cm wider than the widest part of the body on each side in other conditions.

Upon detecting the obstacle, the participant stopped immediately and said “obstacle.” Upon completion of each trial, the experimenter guided the participant to the next starting point. A research assistant changed the size and location of the obstacle for the next trial following a randomized schedule. Each participant completed 12 trials for each of the four obstacle sizes for each of the four experimental conditions: (1) standard-length cane with narrow cane arc, (2) standard-length cane with wide cane arc, (3) extended-length cane with narrow cane arc, and (4) extended-length cane with wide cane arc – a grand total of 192 trials. A trial was recorded as a miss if the participant failed to detect the obstacle with the cane before contacting it with the foot or other part of the body; interrater reliability was 97%.

Variables and analysis—Obstacle detection rate was calculated by dividing the total number of detections by the total number of trials. As was the case in Experiment 1, cane length and cane swing arc width were the primary independent variables of the study.

Analysis procedure for Experiment 2 was similar to that of Experiment 1. We used two-way repeated-measures ANOVA to answer our primary research questions. As a secondary analysis, a three-way repeated-measures ANOVA was used to examine possible interactions

between obstacle's lateral position (center vs off to the side) and the above-mentioned independent variables.

Results

Overall, participants were able to detect 80.3% ($\pm 7.6\%$) of the obstacles on their walking path. The obstacle detection rate with the extended-length cane ($81.9\% \pm 8.5\%$) was not statistically significantly different from that with the standard-length cane ($78.6\% \pm 7.3\%$), $F(1, 14) = 3.72$, $p = .074$, $r = .46$ (see Table 4). The obstacle detection rate with the narrow cane arc ($78.6\% \pm 7.3\%$) was not statistically significantly different from that with the wide cane arc ($81.9\% \pm 9.6\%$), either, $F(1, 14) = 1.93$, $p = .185$, $r = .35$. However, the participants detected the obstacles that were positioned at the center of their walking path ($82.5\% \pm 8.3\%$) at a statistically significantly higher rate than those positioned slightly off to the side ($79.2\% \pm 7.6\%$), $F(1, 14) = 13.16$, $p = .003$, $r = .70$. None of the two-way interactions were statistically significant: (1) length $\times$ cane arc width, $F(1, 14) = 1.52$, $p = .239$, (2) length $\times$ obstacle position, $F(1, 14) = 1.62$, $p = .224$, and (3) cane arc width $\times$ obstacle position, $F(1, 14) = .706$, $p = .415$. The three-way interaction was not statistically significant, either, $F(1, 14) = .06$, $p = .816$.

Overall discussion

Interpretation of the key findings

We found that standard-length cane is better than the extended-length cane, while narrower cane swing arc is more advantageous than wider cane swing arc for detecting drop-offs. In contrast, neither cane length nor cane swing arc width had a significant effect on obstacle detection performance. A possible explanation for standard-length cane's advantage over the extended-length cane in drop-off detection may be related to its larger angle change generated at the moment the cane tip drops to the drop-off surface from the walking surface. For example, when an individual who is 170 cm tall uses a long cane, as prescribed in LaGrow and Long (2011), his cane-holding hand is positioned at approximately 72 cm from the walking surface. When the cane tip drops to the 7.6 cm-deep drop-off – the drop-off depth that showed the largest difference in detection rate between the standard-length and extended-length canes – the angle between the cane and the walking surface changes from 38.9° to 44.0° (difference of 5.1°) with the standard-length cane. In contrast, the angle change is only 3.2° (from 27.7° to 30.9°) when the extended-length cane is used. A larger change in angle between the cane and the walking surface may have allowed the cane user to detect the drop-off more easily when using the standard-length cane compared to when using the extended-length cane. Our result is consistent with the findings of Rodgers and Wall Emerson (2005), who found the standard-length cane to be significantly more advantageous than either longer or shorter canes, but not with those of D. Kim and Wall Emerson (2012). However, such inconsistency might have resulted from the fact that Kim and Wall Emerson's (2012) study used the cane length difference of 25 cm, whereas in this study, we compared the canes that were different in length by 40 cm to fully reflect the range of cane length that is considered to be optimal among different cane users (Kish, 2009; LaGrow & Long, 2011; Willoughby & Monthei, 1998).

One hypothesis that could be proposed to explain the narrow cane swing arc's advantage over the wide cane swing arc is that the difference in lateral cane swing speed may affect the cane user's ability to perceive the change in the angle between the cane and the walking surface. In other words, higher lateral cane swing speed resulting from a wider cane swing arc (since cane users generally do not slow down their stepping speed even when they swing their cane wider) could have made it difficult for the cane user to detect the change in the angle between the cane and the walking surface produced at the moment the cane tip drops to the drop-off surface (Johnson, Johnson, Blasch, & De l'Aune, 1998). However, similar obstacle detection performance between the narrow cane arc and wide cane arc conditions might have resulted from the fact that all obstacles were presented either at the midline or 15 cm off to the side of the midline of the intended walking path. As a result, swinging the cane substantially beyond the widest part of one's body, which, in turn, is beyond 15 cm from the sagittal plane, did not appear to have added any benefit in detecting presented obstacles.

Strengths and limitations

Practice effect was controlled for by the use of Latin square design. In addition, a within-subject design allowed each participant to serve as his or her own control for potential confounding variables such as age, experience, and vision. Furthermore, the two canes used in the study were made to have similar weight and rigidity so that these possible confounding factors would not affect the outcome.

One of the limitations of the study is related to artificial settings. For example, participants trailed a guide rail during their approach to a presented obstacle. Such trailing might have distracted them from the task of obstacle detection. Similarly, the smooth carpeted walkway used in the drop-off detection experiment may not adequately reflect the walking surface blind cane users encounter every day. Another limitation of the study is related to the difference in cane length between the participant's own cane and the canes used in the study. For example, a taller person, who generally uses a longer cane, may have felt more comfortable with the extended-length cane than with the standard-length cane used in this study, whereas a shorter person, who tends to use a shorter cane, might have felt more comfortable with the standard-length cane. Furthermore, a small sample obtained through a nonprobability sampling method limits the generalizability of the study findings.

Practical implications

The effect size for the standard-length cane's advantage over the extended-length cane was large, both in drop-off detection rate (79.5% vs 67.6%, $r = .87$) and in 50% drop-off detection threshold (4.1 vs 6.5 cm, $r = .88$). Given such, a cane user may not want to use a cane substantially longer than the cane length prescribed by the method described in LaGrow and Long (2011), particularly if reliable drop-off detection is important, perhaps due to the individual's poor balance. The effect size for narrow cane arc's advantage over the wide cane arc was also large, both in drop-off detection rate (78.6% vs 68.5%, $r = .82$) and in 50% drop-off detection threshold (4.3 vs 6.4 cm, $r = .83$). Based on this finding, a cane user may not want to swing the cane substantially wider than 3 cm beyond the widest part of the body, particularly if it is important to reliably detect drop-offs. That being said, we do not interpret the findings to suggest that the standard-length cane and narrow cane arc should

always be used for every cane user. Rather, an O&M specialist or a cane user should assess each person's abilities (e.g. walking speed and balance) and traveling environment, as well as the merits and limitations of using the canes of different lengths and swinging the cane in different widths, when determining which cane length or cane swing should be used in a given situation.

Recommendations

Although we employed a conservative approach and used only the tall obstacles (17.8 cm high) – which, if missed, are likely to trip the cane user and cause a fall – the participants still missed approximately 20% of the presented obstacles. This poses a serious safety concern for the vast majority of the cane users (since even a young and athletic cane user is likely to trip and fall over an obstacle that is as high as 17.8 cm) and indicates a need to alter/modify the current cane design and cane use biomechanics to improve the long cane's inherent ability to detect obstacles more reliably. A study that compares the traditional constant contact technique with a modified constant contact technique – similar to what Uslan (1978) suggested – would be beneficial to determine whether moving the cane side to side with the cane tip always pointing the direction of travel can allow more reliable obstacle detection than a traditional pivoting of the cane. In addition, a study that compares a traditional tip (e.g. marshmallow tip) with a tip that has a much larger contact area with the walking surface (e.g. bundu basher tip) would also be helpful to determine whether such design change can substantially improve the cane's inherent ability to detect obstacles more reliably. Given that cane users do not always approach a drop-off (e.g. curb) squarely (i.e. perpendicular to the drop-off edge), a study in which cane users attempt to detect a drop-off as they approach it in an angle (e.g. 45° with the drop-off edge) would also be helpful in improving the generalizability of the study findings. Furthermore, conducting drop-off and obstacle detection studies on actual sidewalk with real curbs and every day obstacles (e.g. construction cones, driveway toys, and bricks) may enhance the practical applicability of the study findings.

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Figure 1.
Two prototype canes: standard length (122 cm) and extended length (162 cm).

Figure 2.
Participant approaching the drop-off on the walkway.

Figure 3.
Interaction between cane arc width and drop-off depth. Error bars indicate standard errors.

Figure 4.
Interaction between cane length and drop-off depth. Error bars indicate standard errors.

Figure 5.
Obstacles of different sizes (diameters of 5.1, 15.2, 25.4, and 35.6 cm).

Figure 6.
Participant approaching the obstacle on the obstacle detection path along the 6.1-m-long guide rail.

Table 1

Participant demographic information (drop-off detection experiment).

Participant no.	Gender	Age	Visual acuity	Onset of VI	Cane use experience	O&M training	Etiology
1	M	27	NLP	Birth	1year	6months (daily)	Unknown
2	F	25	20/400	Age 19	4months	1month (daily)	Uveitis
3	F	61	20/400	Birth	2months	2months (daily)	Stargardt's disease
4	F	56	HM at 2 ft	Age 41	8months	2months (daily)	Unknown
5	F	27	LP	Age 24	1year	4months (daily)	Brain tumor
6	F	54	NLP	Birth	42years	6years (weekly)	Congenital glaucoma
7	M	65	NLP	Birth	45years	1year (weekly)	Retinopathy of prematurity
8	M	65	LP	Age 56	8years	5months (daily)	Optic neuropathy
9	M	21	NLP	Age 12	8years	6years (weekly)	Unknown
10	M	53	20/800	Age 33	9years	5months (daily)	Retinitis pigmentosa
11	F	52	NLP	Age 20	32years	5months (daily)	Diabetic retinopathy
12	F	40	20/800	Age 11	6years	1month (daily)	Stargardt's disease
13	M	31	20/320	Age 26	4years	4months (daily)	Hydrocephalus
14	M	32	LP	Birth	28years	13years (weekly)	Unknown

NLP: no light perception; LP: light perception; HM: hand movement; VI: visual impairment; O&M: orientation and mobility.

Table 2Main effects of cane length and cane swing arc width on drop-off detection ($N=14$).

	50% Detection threshold			Overall detection rate		
	<i>M</i> (cm)	<i>SD</i> (cm)	<i>p</i>	<i>M</i> (%)	<i>SD</i> (%)	<i>p</i>
Cane length						
Standard (122cm)	4.1	1.1	<.001	79.5	6.5	<.001
Extended (162cm)	6.5	1.8		67.6	9.1	
Difference	-2.4	1.3		11.9	7.0	
Cane swing arc width						
Narrow ^a	4.3	1.4	<.001	78.6	7.6	<.001
Wide ^b	6.4	1.6		68.5	8.3	
Difference	-2.1	1.5		10.1	7.2	

SD: standard deviation.^aNarrow cane swing arc is defined as swinging the cane approximately 3 cm wider than the widest part of one's body.^bWide cane swing arc is defined as swinging the cane approximately 30 cm wider than the widest part of one's body on each side.

Table 3

Participant demographic information (obstacle detection experiment).

Participant no.	Gender	Age	Visual acuity	Onset of VI	Cane use experience	O&M training	Etiology
1	M	65	NLP	Birth	45years	1year (weekly)	Retinopathy of prematurity
2	M	32	LP	Birth	28years	13years (weekly)	Unknown
3	F	58	HM at 3 ft	Birth	12years	1month (daily)	Retinitis pigmentosa
4	M	21	LP	Birth	16years	13years (weekly)	Leber's amaurosis
5	M	31	20/320	Age 26	4years	4months (daily)	Hydrocephalus
6	F	52	NLP	Age 20	32years	5months (daily)	Diabetic retinopathy
7	F	54	NLP	Birth	42years	6years (weekly)	Congenital glaucoma
8	M	53	20/800	Age 33	9years	5months (daily)	Retinitis pigmentosa
9	F	31	NLP	Age 3	27years	13years (monthly)	Glaucoma
10	M	37	LP	Birth	33years	13years (weekly)	Optic nerve atrophy
11	M	21	20/800	Birth	16years	13years (weekly)	Glaucoma
12	F	40	20/800	Age 11	6years	1month (daily)	Stargardt's disease
13	M	60	20/400	Age 46	5years	4months (daily)	Diabetic retinopathy
14	M	44	NLP	Age 1	20years	2years (weekly)	Glaucoma
15	F	63	HM at 5 ft	Age 58	8months	3months (daily)	Unknown

NLP: no light perception; LP: light perception; HM: hand movement; VI: visual impairment; O&M: orientation and mobility.

Table 4Main effects of cane length and cane swing arc width on obstacle detection ($N=15$).

	Overall detection rate		
	<i>M</i> (%)	<i>SD</i> (%)	<i>p</i>
Cane length			
Standard (122cm)	78.6	7.3	.074
Extended (162cm)	81.9	8.5	
Difference	3.3	4.5	
Cane arc width			
Narrow ^a	78.6	7.3	.185
Wide ^b	81.9	9.6	
Difference	3.3	7.6	
Obstacle position			
Center	82.5	8.3	.003
Left or right ^c	79.2	7.6	
Difference	3.3	3.4	

SD: standard deviation.^a Narrow cane arc is defined as swinging the cane approximately 3 cm wider than the widest part of one's body.^b Wide cane arc is defined as swinging the cane approximately 30 cm wider than the widest part of one's body.^c Approximately 15 cm off either to the left or right from the midline of the walking path.