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Drop-off detection with the long cane: effect of cane shaft weight and rigidity on performance

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Abstract

Most travellers who are blind rely on a long cane to detect drop-offs on their walking paths. We examined how different cane shaft materials affect drop-off detection performance through providing different vibrotactile and proprioceptive feedbacks to the cane user. Results of the study showed a significant interaction between cane shaft weight and how the cane is used. A heavier cane was advantageous for detecting drop-offs when the individual used the ‘constant contact technique’ – cane tip stays in contact with the walking surface at all times – but not when he used the ‘two-point touch technique’ – cane tip is rhythmically tapped on the surface. In addition, a more flexible cane was advantageous for detecting drop-offs when the two-point touch technique was used but not when the constant contact technique was used. It is recommended that, when blind individuals select a cane shaft material, they consider which long cane technique they use more often.

Practitioner Summary: Long cane shaft material affects how well a blind individual can detect drop-offs. A heavier shaft was advantageous when using the constant contact technique (cane tip stays in continuous contact with the surface), while a more flexible shaft was better when using the two-point touch technique (cane tip rhythmically taps the surface).

Keywords

Biomechanics; perception; equipment design; hand–arm vibration; long cane for the blind

1. Introduction

Although the use of a staff or stick by individuals who are blind for their independent travel has been documented for thousands of years, it was not until the Second World War that modern long cane design and technique emerged (Hoover 1962). How a cane is designed

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and used appears to affect how well a cane user can detect hazards such as drop-offs on the walking path (Bongers et al. 2002; Kim, Wall Emerson, and Curtis 2009, 2010a, 2010b; Rodgers and Wall Emerson 2005a; Schellingerhout et al. 2001).

A long cane has three key parts: grip, shaft and tip. A cane grip is often constructed with rubber, foam or plastic materials in a way similar to how golf club grips are manufactured. The length of the shaft generally ranges from 115 to 165 cm, depending primarily upon the cane user's height (LaGrow and Long 2011). Aluminium, graphite and fibreglass are some of the most commonly used materials for a long cane shaft. The modern long cane was developed during the Second World War and the cane tip was originally cylindrical in shape and made of nylon (Veterans Administration 1964). However, cane tips of various shapes (marshmallow, ball, disc, etc.) and materials (metal, ceramic, plastic, etc.) are now commercially available to blind cane users.

The two primary cane techniques most widely used by blind travellers are the two-point touch technique and the constant contact technique (LaGrow and Long 2011). The two-point touch technique – moving the cane from side to side and touching/tapping the edges of one's walking path in an arc slightly wider than the widest part of one's body – has been the standard long cane technique since its development in the 1940s, while the constant contact technique – sweeping the cane from side to side in an arc slightly wider than the widest part of one's body while keeping the cane tip in contact with the walking surface at all times – is also frequently used by blind individuals. While the two techniques have many similarities, it should be noted that when using the two-point touch technique, the cane tip is lifted off the walking surface and swung to the opposite side between each tap on the surface, whereas when using the constant contact technique, the cane tip stays in constant contact with the walking surface, including while the cane is swung back and forth.

In an attempt to create a framework for measuring blind individuals' ability to get around, Armstrong (1975) categorised mobility performance into two main components: safety and efficiency. Armstrong (1975) included drop-off detection as one of the main measures of safety in this framework. Two decades later, Blasch and his colleagues developed a theoretical framework that explains how the long cane provides environmental information by creating a three-dimensional spatial window (Blasch and De l'Aune 1992; Blasch, LaGrow, and De l'Aune 1996; LaGrow, Blasch, and De l'Aune 1997). That is, by swinging the cane side to side while walking forward, the cane user generates a three-dimensional window through which he previews his environment. This conceptualisation was used as a theoretical framework by several long cane studies in recent years (Bongers et al. 2002; Kim, Wall Emerson, and Curtis 2009, 2010b; LaGrow, Blasch, and De l'Aune 1997; Rodgers and Wall Emerson 2005a; Schellingerhout et al. 2001; Wall and Ashmead 2002). Blasch, LaGrow, and De l'Aune (1996) divided environmental preview into three categories: object preview (detection of obstacles on one's walking path), surface preview (detection of changes in elevation of one's walking surface) and foot placement preview (whether the cane tip has cleared the surface area where the cane user's foot will be placed). Drop-off detection, a key component of the surface preview (Blasch, LaGrow, and De l'Aune 1996), is critical for the safety of blind travellers because missing a drop-off or other changes in

elevation of the walking surface may cause them to fall or accidentally stumble into the collision path of approaching vehicles.

Biomechanical factors appear to affect how well a cane user can detect drop-offs. Kim, Wall Emerson and Curtis (2009, 2010a, 2010b) reported that the cane users were able to detect drop-offs more reliably when they used the constant contact technique than when they used the two-point touch technique. Bongers et al. (2002) found that cane sweep width is negatively correlated with drop-off detection performance ($r = -.632$), but cane-holding hand height ($r = .013$) and how high the cane user lifts the tip (while using the two-point touch technique) were not ($r = -.155$). In addition, our unpublished preliminary study findings (Kim and Wall Emerson 2013) also seem to indicate that the farther away the cane-holding hand is from the cane user's sagittal plane, the better the drop-off detection performance ($r = .297$).

Ergonomic factors also seem to affect how reliably a cane user can detect drop-offs. Kim and Wall Emerson (2012) found that a cane length difference of 10" does not significantly affect the cane user's ability to detect drop-offs when the constant contact technique is used. However, in another study, in which the two-point touch technique was used, similar cane length difference did have a significant effect on drop-off detection performance (Rodgers and Wall Emerson 2005a). These results seem to indicate a possible interaction between the length of the cane and how the cane is wielded. In addition, in a study conducted in a residential neighbourhood, LaGrow, Kjeldstad, and Lewandowski (1988) found no significant difference between different cane tips (cylindrical, curved and round) in how reliably the cane users could detect curbs with the two-point touch technique. However, Pietrowicz (1987) and Robertson (1987) reported that marshmallow tip caused fewer instances of sticking than the pencil tip on a rural road and a residential sidewalk, respectively. It is possible that more frequent sticking has a negative effect on reliable detection of drop-offs since many of such sticking instances may disrupt the cane user's rhythmic cane swing.

Vibrotactile feedback transmitted through a long cane (which is affected by the material of the cane and how the cane is wielded), along with proprioceptive feedback from the wrist and elbow, appears to provide key information to the cane user when previewing the environment, but only a handful of studies have examined this topic. Rodgers and Wall Emerson (2005a) reported that lighter and more rigid cane shafts allowed participants to better discriminate the texture of a grooved surface. In a related study, they also found that overall weight and distribution of the weight along a cane's shaft do not have a significant effect on texture discrimination (Rodgers and Wall Emerson 2005b). In an unpublished master's thesis, Pfothner (1977) compared an aluminium shaft with a graphite shaft and reported that, when impacted by a hammer, aluminium shafts produce lower natural frequencies and the vibration lasted longer than that of graphite shafts (ie the aluminium shaft had lower damping). However, Pfothner did not attempt to relate these vibratory characteristics of the cane shafts to any of the performance outcome measures such as drop-off detection or texture discrimination. Given such, one of the logical next steps is to examine how different cane shaft material characteristics affect cane performance outcomes through providing different vibrotactile and proprioceptive feedbacks to the cane user. The

purpose of this study was to investigate whether the weight and rigidity of the cane shaft affect drop-off detection performance as they interact with the type of cane technique used for the task. The hypotheses were: (1) more rigid cane shafts allow more reliable drop-off detection, (2) heavier cane shafts allow more reliable drop-off detection and (3) there is an interaction between cane shaft weight, rigidity and the type of cane technique used in drop-off detection.

2. Methods

2.1. Participants

Ten male and 5 female adults who were legally blind and had no other disabilities participated in the study. Visual acuities ranged from 20/200 to no light perception. Causes of vision loss included retinopathy of prematurity ($n = 3$), Lieber's Ameurosis ($n = 2$), glaucoma ($n = 2$), retinitis pigmentosa ($n = 2$), diabetic retinopathy ($n = 1$), optic nerve atrophy ($n = 1$), Stargardt's ($n = 1$) and others ($n = 3$). Participants' age varied from 21 years to 65 years (*median* = 40). Visual impairment occurred at the age four or younger for six participants, while it manifested beyond age four for the remainder. Of the sample, five participants used the two-point touch technique more frequently (60–90% of the time), and the remainder used the constant contact technique more often (60–90%). Participants' experience in using the long cane varied from 3 to 45 years (*median* = 13 years). Seven participants stated that they travel independently almost every day, six stated that they travel independently three to six days per week and two stated that they travel independently less than three days a week.

2.2. Cane shaft materials and their characteristics

2.2.1. Cane shaft materials—Four cane shaft materials were selected based on their weight and rigidity so that they are matched on weight and rigidity in a 2×2 matrix: (1) pultruded carbon (light and rigid), (2) poplar (light and flexible), (3) 6061 aluminium (heavy and rigid) and (4) Ultem 2300 (heavy and flexible) (see Table 1). Pultruded carbon is a carbon fibre-based material, manufactured by pulling fibres first through a bath of thermosetting resin and then a heated die, which gives it high rigidity for a low linear density. The pultruded carbon shaft used in this study is hollow and has a tubular cross section of 12.6 mm (Goodwinds LLC). Poplar is a common wood with a low linear density and good flexibility. The poplar shaft used in the study is solid and has a cross-sectional diameter of 12.7 mm (Menards). 6061 aluminium is a common alloy used for a wide range of applications and has a high linear density and rigidity. The 6061 aluminium shaft is hollow and has a cross-sectional diameter of 12.7 mm (McMaster-Carr). Ultem 2300 is a 30% glass-filled polyetherimide. The 30% glass adds strength and rigidity to an otherwise very flexible material. The Ultem 2300 shaft is solid and has a cross-sectional diameter of 15.9 mm (Sterling Plastics Inc.). All shafts were 137.2 cm in length and each shaft's mass was evenly distributed along the length of the shaft.

2.2.2. Rigidity (deflection test)—Initially, each cane shaft material was weighed using an Ohaus Scout II electronic scale. The rigidity of each cane shaft (before the grip and tip were pressed on) was determined by measuring deflection produced by an applied force.

This was done using a cantilevered configuration by adding weight to the free end and recording the deflection caused by a given weight (see Figure 1). One end of each shaft was placed in a clamp on a workbench. A small hole was drilled and an eyelet was placed into the other end where the weights are to be hung. The weight set was an Ohaus-hooked mass set that ranged from 10 to 1000 g. A Keyence LK-G152 laser displacement-measuring device was used on the merits of its precision and the ability to measure displacement without any contact with the objects being measured. The device was set up on a second workbench near the free end of the shaft so that the laser could be directed down onto the top of the spot where the weights were to be added (see Figure 2).

After each shaft was placed into the clamp with 116.8 cm exposed, the laser was zeroed out with no load at the top of the total range. This allowed for approximately 80 mm of range to measure the deflections with the effective range of ± 40 mm of the software used for measuring displacement (LK-Navigator). Weights were added systematically and deflection was recorded for each level of weight. The rigidity of each material was determined by finding the force per amount of deflection. A regression line was fit to each curve to calculate the slope of the line, which represents the rigidity of the material in units of N/m (see Figure 3 and Table 1).

2.2.3. Vibratory characteristics (vibration test)—Vibratory characteristics of each shaft were investigated using an impact test. The testing configuration was similar to that used in the deflection test. Two accelerometers (PCB Piezotronics Inc.) were attached to the shaft: one to the free end of the shaft on the top side of the shaft and the other close to the clamp on the underside of the shaft (see Figure 4). The second accelerometer was placed on the underside to leave space for an impact site. By impacting the shaft near the clamped end, vibrations travel down the shaft to the accelerometer placed on the free end. Change in magnitude of vibration between these two accelerometers at each natural frequency is reported in form of a ratio in decibels (transfer function) in Table 2a. This change in magnitude is shown as an amplification or positive dB values because the free end tends to vibrate more than the clamped end.

The natural frequencies up to 500 Hz were determined from the frequency response function (FRF). According to ASTM E756 (2010), the modal loss factor is the natural frequency divided by the half power bandwidth; the loss factor is related to damping ratio (ζ). The natural frequency (ω_n) is shown in Figure 5 as the local peak on the FRF curve. From there, the magnitude in decibels (dB) was determined as well and the points that are 3 dB less than the peak amplitude of the natural frequency (ω_1 and ω_2). The values for ω_n , ω_1 and ω_2 were obtained using a frequency analysis software (M+P International Smart Office Analyzer). These were plugged into the equation below to determine damping ratio (ζ). Damping ratio at each natural frequency was obtained (shown in Table 2b). In addition, the time it takes the magnitude of the vibration to decay by 99% (99% decay time) is also reported in Table 2b.

$$\frac{1}{2 * \zeta} = \frac{\omega_n}{\omega_2 - \omega_1}$$

2.3. Cane assembly and other apparatus

2.3.1. Cane assembly—A foam golf grip – 25.4 cm in length and 17 g in weight – (Toski Ultralight Putter Grip) was pressed down over one end of each cane shaft (except for the Ultem 2300 shaft). On the opposite end of each cane shaft, a nylon cylindrical tip – 7.5 cm in length and 10 g in weight – (Ambutech MT3050 Slip-on Pencil Tip) was pressed on (see Figure 6). Because of the larger diameter, the Ultem 2300 cane shaft was machined down to the diameter of 12.7 mm so that a grip could easily slide over the shaft. Only the first 25.4 cm of the Ultem 2300 shaft was machined for the grip. Similarly, in order for the cane tip to be pressed on, the Ultem 2300 shaft was machined to a diameter of 12.7 mm on the other end of the shaft for the length of 2.4 cm. A small piece of adhesive tape was added between the nylon tip and the cane shaft so that the tip stayed connected securely on the shaft. Using these procedures, we assembled four canes of equal length made of the following four materials: (1) aluminium, (2) pultruded carbon, (3) Ultem 2300 and (4) poplar.

2.3.2. Other apparatus—Six carpeted plywood platforms (each 2.4 m long, 1.2 m wide and 20 cm high), supported by 5 cm × 10 cm wooden braces, were used to form a 9.8-m-long walkway (see Figure 7). The walkway was 1.2 m wide for the first 4.9 and 2.4 m wide for the latter half. We placed two plywood boards (.8 m long and 1.2 m wide) laid on top of braced rectangular wooden frames against the lengthwise end of the walkway to vary the drop-off depth (2.5–17.5 cm with 2.5 cm increments) from trial to trial. Carpeting on these plywood boards was identical to that on the walkway, which was aimed at preventing participants from using texture and auditory cues for detecting drop-offs. Each trial was also recorded with a digital camcorder (Canon Vixia HF R300 HD).

2.4. Experimental procedure

Each participant signed the informed consent form for the present study approved by the University's Human Subjects Institutional Review Board before participating in the study. Sleep shades and a full-size headphone set (Radio Shack Full-Size Stereo Headphone 33-1225) connected to an MP3 player (iPod Touch 5th Generation) were worn by each participant during all trials. Through the headphone set, rhythmic beats (90 to 110 beats per minute) over a white noise background (recorded by Sound for Life) were played to the participants. The experimenter (a certified orientation and mobility specialist) set the speed of the rhythmic beats in accordance with each participant's relaxed stepping speed and instructed the participant to synchronise the steps to the beats. This instruction was aimed at helping the participants walk at an unchanging pace throughout the trials, limiting the potential confounding effect of walking speed on drop-off detection performance.

Each participant was positioned at the centre of the walkway, squarely facing the drop-off. We randomly selected starting points for different trials (between 4.3 and 9.1 m from the drop-off) to prevent participants from anticipating the drop-off at a predictable distance. Upon receiving a signal from the experimenter, a participant walked towards the drop-off using either the constant contact technique or the two-point touch technique, following a randomised schedule of trials. Participants stopped immediately upon detecting the drop-off and verbally indicated the detection of the drop-off. The experimenter walked behind the participant to help in case of stumbling off the walkway. Upon completion of each trial, the

experimenter guided the participant to the next starting point, walking in an irregular pattern to prevent the participant from knowing how far the next starting point was from the drop-off. The participant had one practice trial for each of the following eight conditions: (1) rigid and heavy cane – aluminium – with two-point touch technique, (2) rigid and light cane – pultruded carbon – with two-point touch technique, (3) flexible and heavy cane – Ultem 2300 – with two-point touch technique, (4) flexible and light cane – poplar – with two-point touch technique, (5) rigid and heavy cane with constant contact technique, (6) rigid and light cane with constant contact technique, (7) flexible and heavy cane with constant contact technique and (8) flexible and light cane with constant contact technique. Each participant completed 16 trials for each of the eight conditions for a total of 128 trials.

A trial was recorded as either a ‘miss’ or ‘detected’. It was recorded 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. Such intervention was necessary to prevent injuries when large drop-offs were presented. Two experimenters scored the trials independently; inter-rater reliability was 98%.

2.5. Subjective preference ranking

Subjective rating of the cane shafts was measured upon completion of all required trials. The following instructions were given to each participant: ‘Please rank the cane shafts (canes) in the order of the most preferred to the least preferred for detecting drop-offs based on your experience with the four canes today’. The most preferred cane shaft was given the score of 1, while the least preferred one received the score of 4.

2.6. Variables and analyses

We used the absolute drop-off detection threshold (50%) and drop-off detection rates to measure the participants’ drop-off detection performance (dependent variable). We calculated the 50% absolute drop-off detection threshold for each experimental condition using the psychometric function described in Gescheider (1997). That is, we fitted a cumulative normal distribution curve to the data points to estimate the drop-off depth that was detected in 50% of the trials. We computed drop-off detection rates by dividing the total number of detections by total number of trials for each experimental condition and for drop-off depth (2.5, 7.6, 12.7 and 17.8 cm). We examined three within-group dichotomous independent variables in this study. They were rigidity (rigid vs. flexible), weight (heavy vs. light) and type of cane technique (two-point touch vs. constant contact).

Upon completing a series of descriptive statistical procedures, we used a fixed-effects model (three-way repeated measures) analysis of variance to examine the main effects and interaction effects of the independent variables on drop-off detection performance. For ordinal data (participants’ preference rankings), analogous nonparametric statistical procedures were used. That is, Friedman’s ANOVA was used to compare preference rankings among the cane shafts, while Wilcoxon tests were used for pairwise *post hoc* tests. We used a significance level of .05 for all statistical tests (two-tailed); Bonferroni correction was used for all pairwise *post hoc* tests ($\alpha = .008$). The statistical powers of *F* tests were .84 or higher when a large effect size ($f = .4$) was assumed (Cohen 1988; Erdfelder, Faul, and

Buchner 1996). Statistical powers of corresponding nonparametric tests are estimated to be slightly lower (Cohen 1962). All statistical analyses, except for power analyses (G*Power Version 3.0.10), were conducted with SPSS version 20.

3. Results

3.1. Main effects

Participants detected drop-offs at a significantly higher rate with the constant contact technique ($M = 82.5\%$, $SD = 8.2\%$) than with the two-point touch technique ($M = 72.9\%$, $SD = 9.8\%$), $F(1, 14) = 27.46$, $p < .001$ (see Table 3). The 50% absolute drop-off detection threshold for the constant contact technique ($M = 1.47''$, $SD = .60''$) was also significantly smaller than that with the two-point touch technique ($M = 2.42''$, $SD = .89''$), $F(1, 14) = 28.61$, $p < .001$. No significant main effects were observed for cane weight, $F(1, 14) = .30$, $p = .595$, or cane shaft rigidity, $F(1, 14) = .51$, $p = .486$.

3.2. Interaction effects

The three-way interaction among rigidity, weight and technique was not significant, $F(1, 14) = 1.05$, $p = .324$; therefore, we examined possible two-way interactions between these variables and their simple effects (Keppel 1991). We found a significant two-way interaction between weight of the cane and the type of cane technique used in drop-off detection, $F(1, 14) = 12.74$, $p = .003$ (see Figure 8). In other words, when using the constant contact technique, participants detected drop-offs at a higher rate with the heavier canes ($M = 85.6\%$, $SD = 9.8\%$) than with the lighter canes ($M = 79.4\%$, $SD = 8.8\%$). However, participants detected drop-offs at a slightly higher rate with the lighter canes ($M = 75.4\%$, $SD = 9.5\%$) than with the heavier canes ($M = 70.4\%$, $SD = 10.9\%$) when using the two-point touch technique. Somewhat similarly, the 50% absolute drop-off detection threshold for the heavier canes ($M = 1.28''$, $SD = .68''$) was smaller than that for the lighter canes ($M = 1.66''$, $SD = .66''$) when using the constant contact technique. However, the difference was minimal between the heavier canes ($M = 2.42''$, $SD = .88''$) and the lighter canes ($M = 2.41''$, $SD = 1.01''$) when using the two-point touch technique.

In addition, there was a significant interaction between rigidity of the cane shaft and the type of cane technique used in drop-off detection, $F(1, 14) = 8.20$, $p = .013$ (see Figure 9). That is, participants detected drop-offs at a slightly higher percentage with the flexible cane ($M = 75.0\%$, $SD = 8.8\%$) than with the rigid cane ($M = 70.8\%$, $SD = 13.4\%$) when using the two-point touch technique. However, drop-off detection rate was very similar between the flexible and rigid canes when using the constant contact technique (flexible cane $M = 82.1\%$, $SD = 9.0\%$; rigid cane $M = 82.9\%$, $SD = 8.9\%$). There was no significant interaction effect of cane weight and cane shaft rigidity on drop-off detection performance, $F(1, 14) = .74$, $p = .405$.

3.3. Preference ranking

There was a statistically significant difference in preference ranking (1 being the highest and 4 being the lowest) among the cane shafts, $\chi^2 = 34.36$, $p < .001$. Participants ranked the light flexible (*Median* = 1, *Range* = 2) cane shaft as the most preferred cane shaft, which was

followed by the light rigid (*Median* = 2, *Range* = 1), heavy rigid (*Median* = 3, *Range* = 2) and heavy flexible (*Median* = 4, *Range* = 1) cane shafts. Post hoc analyses revealed that the ranking of the light flexible cane shaft was significantly different from that of heavy flexible and that of heavy rigid cane shafts, respectively ($Z = -3.50, p < .001$; $Z = -3.25, p = .001$). Similarly, the ranking of the light rigid cane shaft was significantly different from that of the heavy flexible and that of heavy rigid cane shafts, respectively ($Z = -3.45, p = .001$; $Z = -3.51, p < .001$). All other pairwise comparisons, including the comparisons between the light flexible and light rigid cane shafts and between the heavy rigid and heavy flexible cane shafts, did not produce significant results.

4. Discussion

Heavier canes were more advantageous in detecting drop-offs when using the constant contact technique but not when using the two-point touch technique. In contrast, more flexible canes were slightly better for detecting drop-offs when using the two-point touch technique, but the drop-off detection rates of the flexible and rigid canes were very similar when using the constant contact technique. The larger downward force produced by heavier canes appears to have made it easier for the cane users to notice when the cane tip started dipping lower than the walking surface as it passed the edge of the walking surface (falling towards the drop-off surface). Unlike when using the constant contact technique, however, with the two-point touch technique, the need to exert a greater force (due to the heavier cane's larger moment of inertia, as shown in Table 1) to rhythmically lift the cane tip and the consequent fatigue on the wrist joint might have diminished the proprioceptive sensitivity to the increase in ulnar deviation that occurs at the moment the cane tip drops below the walking surface (Allen, Leung, and Proske 2010; Gooley et al. 2000). It is also possible that better drop-off detection performance with heavier cane shafts when using the constant contact technique is a result of longer vibration decay time of heavier cane shafts than of lighter cane shafts. That is, the mean 99% decay time (time it takes for the vibration magnitude to decay by 99%) for heavier cane shafts was 1.52 s (*SD* = .28 s) while that for lighter cane shafts was .76 s (*SD* = .07 s). It appears possible that longer vibration decay time allowed the cane user to more easily notice the cane tip drop, given that longer vibration signals tend to be easier to detect than shorter signals (Gescheider, Bolanowski, and Verrillo 2004). However, when using the two-point touch technique, longer decay time might not have been helpful since the vibration decay time was longer not only for the tap on the drop-off surface but also for a series of taps on the walking surface as the cane user approached the drop-off.

Better drop-off detection performance with more flexible canes over the more rigid canes when using the two-point touch technique might have resulted from different frequency spectra produced by the cane shafts of different rigidities. That is, the presence of a larger number of natural frequencies in the lower frequency range (3–120 Hz) produced by more flexible cane shafts might have helped the cane users detect the vibrations from the cane more easily. Although many studies showed that the most sensitive vibrotactile frequency range for palms (for detecting vibration displacement) tends to be 100–150 Hz (Brisben, Hsiao, and Johnson 1999; Israr et al. 2007; Morioka and Griffin 2009), most of them did not include frequencies lower than 25 Hz, despite the fact that the threshold contours produced

in the studies that included lower frequencies show a pattern of noticeable downward turn (becomes more sensitive) as the frequency gets lower than 30–40 Hz (Bolanowski et al. 1988; Delemos and Hollins 1996; Morioka and Griffin 2005). Presence of these prominent low-frequency peaks produced by more flexible cane shafts might have led the cane user to detect drop-offs more easily when using more flexible canes. We also examined vibration decay time (99%) to see whether the flexible cane shaft's advantage over rigid cane shafts may be related to decay time. However, the mean vibration decay time for more flexible cane shafts ($M = 1.0$ s, $SD = .38$ s) was similar to that for more rigid cane shafts ($M = 1.2$ s, $SD = .50$ s).

Given the advantage of heavier canes when the constant contact technique is used to detect drop-offs, cane users may want to use a heavier cane if they primarily use the constant contact technique for travel. On the other hand, if the two-point touch technique is the primary technique used for travel, cane users may want to use a lighter cane to more reliably detect drop-offs. Similarly, given the advantage of more flexible canes when the two-point touch technique is used to detect drop-offs, cane users are recommended to use a more flexible cane if the two-point touch technique is their primary technique for travel. Cane users may not need to be concerned about how flexible the cane is if the constant contact technique is their primary cane technique. In addition, if detecting small drop-offs (eg one inch drop-offs) is important, perhaps because the individual has poor balance, it is recommended that the individual use the constant contact technique with a heavier cane. On the other hand, if detecting small drop-offs is not of critical importance, perhaps because the cane user is well coordinated and can easily recover from a possible momentary loss of balance caused by such drop-offs, the rigidity and weight of the cane do not seem to matter much, although the use of the constant contact technique will significantly enhance the cane user's ability to detect such small drop-offs. However, we do not claim that a heavier cane or a more flexible cane should always be used in the situations described above. Similarly, we do not suggest that the constant contact technique should be the primary cane technique taught to every long cane user. Rather, O&M specialists should assess each person's physical abilities (eg whether the person can handle a heavier cane), age and travel environment, along with the merits and limitations of each type of cane shaft material and cane technique, for appropriate cane material and cane technique selection.

We controlled for order effect by assigning participants to different conditions using a balanced Latin square counterbalancing method. In addition, the repeated-measures study design allowed each participant to serve as his or her own control for potential confounding. One of the limitations of the study related to the vibration tests is that vibratory characteristics of the canes when held in a hand may be different from those generated when the shafts were gripped by a vice. Another limitation of the study results from the fact that the sample was obtained through a nonprobability sampling method, which limits the generalisability of the findings. In addition, although all the participants had been taught both cane techniques during their previous O&M training, which cane technique the participants used as the primary cane technique might have affected the results. However, a previous study indicates that such effect is likely to be minimal (Kim, Wall Emerson, and Curtis 2010c).

Future cane studies may include investigation of how other ergonomic factors, such as cane tip and cane weight distribution, affect drop-off detection performance. Examination of how other biomechanical factors, including the width of the cane arc, position of the cane-holding hand and rhythmic cane–gait coordination, affect drop-off detection may also have important practical implications for cane users and O&M specialists. Furthermore, it is necessary to examine multiple aspects of users' performance with a long cane, including obstacle detection, texture discrimination and travel efficiency, to determine the overall effectiveness of cane travel.

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Figure 1.
Deflection measurement schematic.

Figure 2.
Set-up for deflection testing with Keyence LK-G152 laser displacement-measuring device.

Figure 3.
Rigidity of cane shafts.

Figure 4.
Vibration test set-up.

Figure 5.
Damping ratio calculation from the FRF curve.

Figure 6.
Canes assembled with four different materials: from the top, aluminium, Ultem 2300, pultruded carbon and poplar.

Figure 7.
Participant approaching the drop-off on the 9.8-meter-long walkway.

Figure 8. Interaction between cane shaft weight and type of cane technique used in drop-off detection. Note: Error bars indicate standard errors.

Figure 9.
Interaction between cane shaft rigidity and type of cane technique used in drop-off detection.
Note: Error bars indicate standard errors.

Table 1

Material properties and dimensions of the four cane shafts.

	Pultruded carbon	Poplar	6061 aluminium	Ultem 2300
Category	Light rigid	Light flexible	Heavy rigid	Heavy flexible
Length (cm)	137.2	137.2	137.2	137.2
Outside diameter (mm)	12.5	12.7	12.7	15.9
Inside diameter (mm)	10.4	Solid	6.5	Solid
Linear density (g/cm)	.6	.7	2.5	3.0
Assembled cane weight (g) *	112	118	376	420
Moment of inertia (kg·m ²) **	.012	.015	.054	.053
Moment of inertia (kg·m ²) ***	.056	.064	.183	.212
Rigidity (N/m)	149.5	34.5	153.0	35.4

* Assembled cane weight includes the weight of the cane tip (10 g) and the grip (17 g).

** Moment of inertia about each shaft's centre of gravity.

*** Moment of inertia about the midpoint of the grip of each assembled cane.

Table 2a

Vibratory characteristics of cane shafts.

Shaft material	Category	Natural Frequencies (0–500 Hz)							Transfer Functions (dB)						
		F1	F2	F3	F4	F5	F6	F7	TF1	TF2	TF3	TF4	TF5	TF6	TF7
6061 Aluminium	Heavy and rigid	7	45	130	254	418	NA	NA	43.2	24.4	24.3	16.9	11.4	NA	NA
Pultruded carbon	Light and rigid	15	89	257	496	NA	NA	NA	39.5	19.9	17.2	10.8	NA	NA	NA
Uitem 2300	Heavy and flexible	3	21	58	114	188	282	392	19.4	34.5	19.1	14.3	10.0	6.7	4.0
Poplar	Light and flexible	6	41	114	223	364	NA	NA	37.2	27.4	18.5	12.8	8.9	NA	NA

Notes: F1 through F7 refer to the first seven natural frequencies (up to 500 Hz). TF1 through TF7 indicate the change in vibration magnitude from where the cane shaft was struck by the hammer to the free end of the cane shaft at respective natural frequencies.

Table 2b

Damping characteristics of cane shafts.

Shaft material	Category	Applied force (N)	Damping ratio ($\zeta \times 100$)							99% Decay time (seconds)	
			D1	D2	D3	D4	D5	D6	D7	M	SD
6061 Aluminium	Heavy and Rigid	96	1.47	1.11	.27	.80	.34	NA	NA	1.70	.06
Pultruded Carbon	Light and Rigid	86	1.53	1.05	.45	.34	NA	NA	NA	.79	.05
Uitem 2300	Heavy and Flexible	90	2.61	.97	.83	1.39	.79	.65	.71	1.33	.30
Poplar	Light and Flexible	93	3.15	1.29	1.08	.93	.91	NA	NA	.73	.09

Notes: Damping ratio refers to the coefficient of damping (ζ) at a given natural frequency. DF1 through DF7 indicate the coefficients of damping at respective natural frequencies. Ninety-nine per cent decay time is the time it takes the magnitude of the vibration to decay by 99%.

Table 3

Main effects of cane weight, cane rigidity and type of cane technique used in drop-off detection.

Variable	50% Detection threshold (cm)				Overall detection rate (%)			
	<i>M</i>	<i>SD</i>	<i>F</i>	<i>p</i>	<i>M</i>	<i>SD</i>	<i>F</i>	<i>p</i>
Rigidity			.34	.571			.51	.486
Rigid	1.91	.76			76.9	10.4		
Flexible	1.98	.65			78.5	8.4		
Difference	-.07	.45			-1.6	9.0		
Weight			2.71	.122			.30	.595
Heavy	1.85	.64			78.0	8.7		
Light	2.04	.73			77.4	8.5		
Difference	-.19	.29			.6	4.5		
Technique			28.61	<.001			27.46	<.001
TT	2.42	.89			72.9	9.8		
CC	1.47	.60			82.5	8.2		
Difference	.95	.69			-9.6	7.1		