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Materials Testing in Long Cane Design: Sensitivity, Flexibility, and Transmission of Vibration

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Abstract: Different materials that are used in manufacturing long cane shafts were assessed for their ability to transmit vibration and their sensitivity to tactile information, flexibility, and durability. It was found that the less flexible a cane shaft is, the better it transmits vibrations that are useful for discriminating surface textures and that shafts with less weight transmit energy at higher natural frequencies. A combination of decreased flexibility and decreased weight in a cane appears to optimize the cane's usefulness in discriminating the characteristics of surfaces.

The authors would like to acknowledge the late Emerson Foulke for his role in the conceptualization and performance of the original research leading to this article. Dr. Foulke was a leader in the study of perceptual factors in nonvisual mobility and is sorely missed.

During the development of the modern form of the white cane, wooden canes were found to be unwieldy, short, heavy, and poor conductors of information (Hoover, 1946, 1962). Tubes of drawn aluminum reduced the weight of canes from about 12 ounces for wooden canes to about 6 ounces (Hoover, 1946), maintained durability, and increased the conductivity of vibrations (Ball, 1964). However, after the aluminum long cane was created, continued investigation of ways in which the cane could be improved was advocated (Hoover, 1962; Suterko, 1967), since the long cane is arguably the most effective mobility aid for persons who are visually impaired (Foulke, 1975).

The long cane can impart information, such as breaks in a surface, the roughness of a surface, or the direction of grooved marks. Simply holding the cane, through the angle of the wrist, can specify information like the distance to the ground (Chan & Turvey, 1991). More useful information requires exploration and self-movement through the environment (Solomon, 1988; Turvey, Burton, Pagano, Solomon, & Runeson, 1992). Dynamic touch is necessary to obtain useful information from the environment (Gibson, 1962).

As a cane tip taps or drags on the ground, reaction waves travel up the shaft like waves in a pool of water after a stone is dropped in. The wave of energy transfers along the cane from the point of contact up to where it can be felt by the hand that is holding the cane (Brisben, Hsiao, & Johnson, 1999). In a solid object, such as a cane, two types of mechanical waves are possible: longitudinal and transverse (Roller & Blum, 1981). Longitudinal waves result from particles in the cane vibrating parallel to the direction of energy (such as along the cane shaft), as in a Slinky toy. Transverse waves result from particles in the cane vibrating perpendicular to the direction of energy like vibrations in a guitar string (Gopa, Sanjit, & Srividya, n.d.).

The combination of transverse and longitudinal waves creates "deformations" in the skin and muscles of the hand at the point of contact with the cane grip. Surface characteristics, such as the location and slant and the weight and rotation of the long cane and how the cane is moved, all affect the deformation of skin and muscle in the hand and arm (Chan & Turvey, 1991). This tissue deformation is translated by the perceptual system into a representation of environmental features, such as hardness and roughness of a surface or the size and shape of an object.

Waves can be generally characterized by their frequency and velocity. The frequency is the number of oscillations made by vibrating particles each second. The velocity is the distance covered by the wave over time: $\nu = \lambda/T$ or $\nu = f\lambda$, where λ = wavelength, T = time period of oscillation, and f = wave frequency. The wavelength is the distance covered by the wave in one period of vibration of the particle oscillators in the wave (Roller & Blum, 1981).

A wave's velocity in a medium is governed by the density and elasticity of the medium. The velocity of longitudinal waves is determined by the equation $\nu = E/\rho$, where E = Young's modulus of elasticity and ρ = the density of the medium. Aluminum, for example, has Young's modulus = 70,000,000,000 N/m^2 and density = 2710 kg/m^3. Young's modulus is calculated through the equation $E = (\mathit{force} \times \mathit{initial\_length})/(\mathit{length\_change} \times \mathit{area})$ (Arfken, 1985). The velocity of transverse waves in a medium is determined by the equation $\nu = \mu/\rho$, where μ = the shear modulus and ρ = the material's density. The shear modulus is a measure of the material's rigidity and can be derived from the elasticity through the equation $\mu = E/2(1 + \nu)$, where ν = the Poisson ratio of the material (Arfken, 1985). These equations indicate that the greater the elasticity or rigidity of a material, the faster a wave travels through it, whereas the greater the material's density, the slower a wave travels. Note that greater elasticity will create faster longitudinal waves, while greater rigidity will create faster transverse waves.

The intensity of a wave traveling in a rod is given by the equation Intensity = $\frac{1}{2}(\nu\rho\omega^2 r^2)$, where ν = velocity, ρ = the density of the medium, ω = the angular frequency of each oscillator, and r = the amplitude. So, intensity is proportional to the square of the amplitude of the vibration. Thus, a wave is more intense if it is moving faster, the material is less dense, the angular frequency is higher, and the amplitude of the wave is high (Gopa et al., n.d.). That is, higher-frequency vibrations in less dense, more elastic material will create more intense vibrations that should be felt more easily by a person who is holding a cane.

The type of material that the shaft is made of affects the elasticity and density of the cane and, therefore, how reaction waves are transmitted through the shaft. The relationship between the flexibility and rigidity of the shaft and the transmission of surface characteristics has been examined in several experiments. In most of these experiments, flexibility was assessed by comparing canes with rigid shafts to canes with segmented shafts, perhaps because canes with jointed sections experience more flexibility through "play" at the joints.

Schultz (1985) found that rigid and sectioned cane shafts did not differ in their ability to discriminate between sandpaper of different grades of roughness. Drouillard (1967) reported that the participants' ability to discriminate among carpeted, linoleum, wood, and Formica surfaces was considerably better with a rigid cane than with either of three collapsible canes. Walraven (1982) also noted that lighter and more rigid canes were better for identifying surfaces. Most of the canes he studied were nonrigid; the only rigid ones were made of fiberglass. The results of these studies are inconclusive, since flexibility was often not the principal characteristic that was studied and hence was not always specified. Foulke (1967), however, asked participants (four veterans who were blind) to attempt to identify the roughness of four different surface types using three aluminum canes that varied only in their flexibility. He found that the discrimination of roughness improved as flexibility decreased, but only four participants were observed, and a wider range of shaft flexibilities needs to be tested to evaluate fully the effect of the flexibility of a cane on the identification of the roughness of surfaces.

Schenkman (1986) tested 32 long canes, made in five countries, including folding canes, rigid shafts, and telescoping canes, as well as different grips, lengths, and tips. Schenkman had 10 sighted, blindfolded participants tap twice with each cane on an assortment of surfaces, including asphalt, concrete, linoleum, and sand. The participants were not allowed to sweep or drag the cane on the surface. The results indicated that the participants were not able to discriminate better among the surfaces using one cane as opposed to another.

While the flexibility of a shaft may affect how surface information is conveyed to a cane user, it may also affect how the cane withstands stress. A long cane experiences impact forces every time it taps the ground, but it can also experience extreme bending stress when it is caught between a door and its jamb, in a sidewalk grating, or in a bus door. Because a blind pedestrian with a broken cane could be in a dangerous situation without an adequate tool for gathering information about the environment, it is important to determine the resistance to stress of different cane materials. We conducted a series of experiments to investigate how different materials, varying in flexibility and weight, affect the detection of differences in the roughness of two surfaces and resist bending stress. The materials that we compared were carbon fiber (graphite), fiberglass, and aluminum--three of the most commonly used materials in the manufacture of long cane shafts (Tony Russell, Ambutech, personal communication, February 4, 2004).

Experiment 1: Sensitivity as a function of flexibility

Method

Participants and equipment

To investigate the sensitivity of the long cane as a function of flexibility, we constructed four canes from different materials (vinyl, fiberglass, aluminum, and carbon fiber), so that the canes differed primarily in their flexibility. Flexibility was measured by determining how far one end of a cane could be moved, while the other end was held stationary, before the shaft broke or became permanently bent. Flexibility was tested on the materials before the canes were constructed. The canes were fitted with new nylon "straight" tips and golf club-style grips. Table 1 lists the characteristics of the four canes. Note that the weights of these canes, which were not exactly equal, might have influenced the flexibility of the canes.

The participants were eight sighted students who were drawn from an introductory psychology class at a university. A two-choice discrimination task was used in which the participants examined, with the canes, two metal plates that differed only in roughness and identified the rougher of the two surfaces. To ensure that the participants based their judgments only on information they received from the cane, each participant wore a sleep shade and a pair of monoheadphones (Foster RDF 208) that were connected to a Grason-Stadler white-noise generator (Model 455B) delivering 75 dB of white noise.

The surfaces were two aluminum plates, 9 inches by 6 inches by 1⁄2 inch, whose surfaces were milled with parallel grooves that were perpendicular to the plates' long edges. Grooves covered an area 3 inches wide, centered on the plate to provide a smooth surface 3 inches wide on either side of the grooved surface. Pilot testing found that a 75% correct identification criterion was met if the grooves on each plate contained six grooves that were one-quarter inch wide, separated by islands that were one-quarter inch wide. One plate had grooves that were 0.0105 inch deep, and the other plate had grooves that were 0.0125 inch deep. This difference in depth produced the differential roughness effect.

Procedure

The participants were acquainted with the task in a brief practice session, put on the sleep shades and headphones, scanned each surface with the cane tip, and indicated which of the two surfaces felt rougher. They could vary their scanning rate and force of the cane, but after they examined both plates, they were not allowed to return to a plate for further examination. Each trial consisted of one discrimination between the two plates. Each participant experienced three blocks of 40 trials, with each of the four canes used 10 times in each block, so that each cane was used 30 times in all. The order in which the plates were examined was varied randomly from trial to trial and in each block; half the participants used the four canes in one order, and the other half used them in a different order.

Results and discussion

Overall, the carbon-fiber cane showed the most correct discriminations, and the vinyl cane showed the least. An analysis of variance indicated a significant relationship between the flexibility of the shaft and the number of correct discriminations ($F(3,5) = 13.94$, $p = .007$). A Tukey test, comparing the average correct discriminations for each material with that of each other material, indicated that the number of correct discriminations increased significantly from vinyl to fiberglass to aluminum canes before increasing even more with the use of the carbon-fiber cane. This progression had a significant quadratic component ($F(1,7) = 10.14$, $p = .015$), indicating that the increase in the number of correct detections between the aluminum and the carbon-fiber canes was significantly more than the increase between the vinyl and the fiberglass canes.

The flexibility factor was essentially halved when the participants went from one cane to the next in the sequence (vinyl, fiberglass, aluminum, and carbon fiber) (see Table 1). This linear decrease in flexibility fits with the linear increase in sensitivity ($F(1,7) = 38.18$, $p \leq .001$), except for the exceptional performance of the carbon-fiber shaft. The tight correspondence of trends between the flexibility of the shafts and detection measures supports our contention that other minor differences in other cane characteristics were not major factors in determining sensitivity.

Experiment 2: Canes' responses to vibration

Method

Equipment

Assuming that flexibility and the transmission of vibrations are connected, we tested the shaft materials that were used in the previous experiment to evaluate their transmission of vibration. One set of cane shafts and three sets of canes were tested for their response to induced vibration. The set of shafts included a carbon-fiber, a fiberglass, and an aluminum shaft. The carbon-fiber shaft was tapered from 5/8 inch to 3/8 inch, and the fiberglass shaft was tapered from 1/2-3/8 inch. The aluminum shaft was a section of Series 6063/T-832 aluminum tubing with a uniform diameter of a half inch and a wall thickness of .049 inches. All three shafts were 54 inches long and had neither grips nor tips attached.

The first set of canes that were tested were made of the same three shafts described earlier but fitted with straight nylon tips and cylindrical plastic grips (the National Federation of the Blind, NFB, Type 2 cane). The second set of five canes were constructed by cutting 55-inch lengths of Series 6006/T-6 aluminum tubing (wall thickness = .028 inches) and adding golf club-style grips and nylon tips. Lead weights were attached to the shafts so that the total cane weights were 175 grams (about 6 ounces), 219 grams (about 8 ounces), 263 grams (about 9 ounces), 307 grams (about 11 ounces), and 351 grams (about 12 ounces), and the shafts balanced at the midpoint. The third set of canes were the four canes from the previous experiment in which flexibility was varied.

Procedure

The canes were held by a table vise, 10 inches along the shaft on the grip end. Twelve inches from the tip end of each shaft, an accelerometer (PCB Piezotronics, Model 303A03) was fixed to the shaft with wax. An accelerometer is a device that measures changes in acceleration by using microelectromechanical systems, such as very small springs, built onto semiconductor chips. Vibration was induced by striking the shaft with an impact hammer (PCB Piezotronics, Model 482A) on whose striking surface a force transducer was mounted. The accelerometer and force-transducer outputs were sent to separate signal conditioners and then to a GenRad Digital Test System (Model 2515). The conditioners took the signals output by the accelerometer (changes in acceleration of the cane shaft over time) and the force transducer (amount of force applied to the shaft by the hammer) and modified them so that they could be understood by the GenRad Digital Test System and combined to create a power spectrum for vibrations within the cane shaft. The GenRad Digital Test System averaged the force transducer and accelerometer signals to derive a power spectrum, which was plotted as acceleration amplitude versus frequency.

Because the average applied force was fairly constant, differences in the distribution of energy in different power spectra can be attributed to differences in the canes and cane shafts. Each shaft was struck where the cane or shaft was gripped by the vise and measured at a point near the tip to maintain a more constant applied force and to limit differences in the amount of bending response to the initial blow. The experimenter struck each cane shaft five times with the impact hammer, 4 inches from the point at which it entered the jaws of the vise. The five measures of striking force and shaft acceleration were averaged because it was not possible to hold the striking force completely constant.

Results and discussion

To control for extraneous components in the complex vibrations that were created by the hammer strikes, the GenRad Digital Test System computed a coherence function for each peak frequency in a power spectrum. Strong and coherent frequency peaks indicated primary vibrations, while smaller, less coherent peaks resulted from resonant effects. Peaks with coherence functions of less than .90 were considered unreliable and were rejected as indicators of resonant frequency.

Frequencies in the power spectra extended from 0 Hz to about 300 Hz. Detection thresholds rise steeply below and above the range of 80 Hz to 250 Hz (Brisben et al., 1999; Johansson, Landstrom, & Lundstrom, 1982), so this range is likely to contain frequencies that are useful for conveying surface information to a pedestrian who is blind. A "natural frequency" is any frequency at which an object will vibrate freely when set in motion. Table 2 presents the first four coherent natural frequencies for each cane up to about 300 Hz. Space and clarity preclude the display of the full power spectra. Frequency peaks lower than 20 Hz tended to have coherence functions of less than .90.

The carbon-fiber shaft had higher natural frequencies than did the aluminum shaft, which had higher natural frequencies than did the fiberglass shaft. The same pattern of results was evident for these shafts when they were fitted with tips and grips, with an overall lowering of the natural frequencies. In the canes on which the weight was varied, natural frequencies increased as the weight of the canes decreased. The four canes that varied in flexibility increased in natural frequencies as their flexibility decreased. The four canes in this experiment were ranked in the same way as they were in the previous experiment. This ranking may indicate that a cane's flexibility has much to do with response to vibration, with a less flexible cane transmitting more useful vibrational information.

The results show that the frequencies at which a cane resonated depended on such characteristics as weight and flexibility. When these results are considered with the results from previous experiments in this series, it is tempting to draw the conclusion that the effectiveness of canes is maximized by minimizing their weight and flexibility. In this connection, the finding that decreasing a cane's weight and flexibility increases all its natural frequencies is noteworthy. However, the evidence at hand is not yet sufficient to warrant such a broad conclusion. There are some limitations to the results of this experiment. For example, the canes in Set

4 were 4.5 inches shorter than were the canes in Set 2, which may have influenced the resonant frequencies. Also, the results for the canes in Set 3 may have been due, in part, to how the extra weights were attached to the shafts.

This experiment is only the first step in determining the usefulness of the vibration that is sensed by the hand that holds the cane. The links between the flexibility of the shaft and the conduction of vibration, as well as discrimination of surfaces, do not indicate how a person holding a cane will perceive or be able to interpret and act upon information that is conveyed by vibrations within a cane. Psychophysical tests that alter vibrational information to a cane held by a person need to be performed to illustrate the practical implications of the finding that canes of different materials, weights, and lengths have different vibrational properties.

Experiment 3: Shafts' resistance to bending stress

Method

Equipment

Three cane-shaft materials were tested: carbon fiber, fiberglass, and aluminum. The carbon-fiber and fiberglass shafts were the shafts that are used in NFB Type 10 and Type 2 canes. The aluminum shaft was the type that is used on many commercially made long canes. Testing was conducted on a Material Test System (MTS) (Model 810). The cane shafts rested on two horizontal steel rods that were separated by 3 inches and mounted on a platform that was locked into place on a lower hydraulic head, which was also locked into place. Above the cane shaft was a third steel bar, parallel to the two support rods and halfway between them. This bar was mounted on a platform that could be hydraulically raised and lowered through settings on the MTS Microconsole Control Unit (MCU) (Model 458.20). When the cane shaft was pressed between the upper bar and the lower bars, this force was measured by a force transducer, and the changes in displacement and pressure over time were automatically plotted using a chart recorder

(Model 7030A, F. L. Moseley Company).

Procedure

Each shaft was placed on the two support bars of the MTS, and the upper bar was lowered until a minimal force was indicated. The bar was then raised slightly to a position that was taken as the zero-force position. The shaft was then subjected to a downward displacement of 0.056 inches each second for 9 seconds, for a total displacement of a half inch, well beyond the tolerance of all three shafts. As a reliability check, the aluminum shaft material was tested twice. The two tapered shafts may not exhibit the same resistance to stress at each end, so these types of canes were tested twice at each end.

Results and discussion

The chart recorder calculated the stiffness of each shaft by comparing how much pressure it took to bend the shaft a given amount. Table 3 shows the force that was observed at each of eight displacements for each of the three cane shafts. Since the force that was observed at each displacement generally increased up to .1 inch, the first five entries are given in increments of .02 inch. Beyond .1 inch of displacement, the force decreased sharply or remained stable, so the last three entries are in increments of .05 inch. For each of the tapered canes, the results for the two shaft diameters were nearly identical, and at each shaft diameter at which tests were made, the two sets of measures were also nearly identical, so only the first set of measures for each cane at the tip end are reported.

The aluminum shaft withstood much more force than did the other shafts. In addition, while the aluminum shaft was permanently deformed above .1 inch, the fiberglass and carbon-fiber shafts broke. The values in Table 3 for the fiberglass and carbon-fiber shafts after they broke reflect additional pressure continuing to press against and deform the remaining portions of the cane material within the device. Measurement of the shaft's resistance to bending (stiffness) was calculated as force divided by displacement. The aluminum cane's stiffness was found to be 8,000 pounds per inch, the carbon-fiber cane was 3,300 pounds per inch, and the fiberglass cane was 2,200 pounds per inch. (Since stiffness is nonlinear in this case, these values should be viewed as estimates.) Although the force observed at each displacement increased for the first few increments, it fell sharply thereafter, thereby making obvious the point at which the elastic limit was exceeded. However, the significance of the difference in force at which cane shafts broke or permanently deformed is unknown. The fiberglass shaft withstood only 15 more pounds of force than did the carbon-fiber shaft, and even though the carbon-fiber shaft broke at a lower force than did the fiberglass shaft (120 pounds versus 135 pounds), it was more resistant to bending (3,300 pounds per inch versus 2,200 pounds per inch). The aluminum shaft reached the highest force levels before ending (420 pounds) and had the most resistance to bending or stiffness (8,000 pounds per inch). The measurements of force that are reported in Table 3 indicate that as displacement was increased, force generally increased for displacements of less than .1 inch. Beyond .1 inch of displacement, force continued to increase for the aluminum shaft and decreased for the carbon-fiber and fiberglass shafts because the carbon-fiber and fiberglass shafts had broken or cracked.

The measurement of the resistance of different cane shafts to bending was investigated in the preliminary stage of this study. Only three materials were tested, and only one test--the change in force that was observed as displacement increased--was conducted. Although the results of this test identified a cane shaft material that was more resistant to bending stress than were others, it did not indicate which cane material is best suited for making long canes. Although the aluminum shaft withstood greater force and exhibited greater resistance to bending than did the other two shafts, it weighed twice as much. There is a trade-off between having a more durable cane and a cane that weighs more. If the results of the previous experiments hold true that lighter canes also increase sensitivity, the choice of a more durable shaft may lessen the transmission of vibration through the shaft.

General conclusions

The results of these experiments indicate that the material that is used in a cane shaft can affect the usefulness of the cane. The resistance of a shaft material to bending forces and the point at which a shaft will deform or break may be useful information for a traveler. Knowing that an aluminum shaft will bend before breaking while a fiberglass or carbon-fiber shaft will break and knowing the approximate levels of stress at which these events will occur may influence the type of cane a traveler chooses.

That the fiberglass shaft exhibited the least resistance to bending indicates that it is more rigid and therefore may be better at transmitting vibrations. That the carbon-fiber shaft broke at the lowest level of force indicates rigidity, which, combined with its overall lower weight, may also indicate its increased transmission of vibration and greater sensitivity. The aluminum shaft weighed twice as much as did the other two shafts but was more durable in the stress tests. Although this question can be answered only by an individual cane user, O&M specialists should consider which is more important to the long cane user: resistance to bending, breaking point, weight, or sensitivity? By knowing the characteristics of a cane's material and how these characteristics may influence the use of a cane, a traveler or instructor can make a more informed decision about what kind of cane to use. A person may even change to canes of different materials according to what he or she is doing or where he or she is traveling.

A more widely applicable finding is that less flexible shafts afford better discrimination of the characteristics of surfaces. The connection between more rigid shafts and the transmission of higher natural frequencies suggests an avenue for further exploration. It may be that a more rigid shaft, as well as a lighter cane, will assist in the transmission of these higher natural frequencies. While more research on this connection is needed, the implication is that a shaft that is made of less flexible material and has slightly less weight than other canes will heighten the discrimination of the textures of surfaces. It may be that the joints of a cane that is made up of several sections introduce enough flexibility to the shaft so that sectioned canes will have less of an ability to discriminate among textures. Of course, having a nonfolding cane or a heavier cane involves other trade-offs that a traveler would have to factor into the decision of what cane to use.

These investigations into the primary characteristics of long canes (resistance to stress, flexibility, and the transmission of vibration), in concert with findings regarding the effects of the length and weight of shafts (see Rodgers & Wall Emerson, 2005) illustrate the importance of ongoing experimentation with the effect of cane designs on performance. These exploratory data indicate that there are enough differences among canes that a concomitant influence on performance seems likely. Continuing research in this area is suggested so that travelers who use long canes can make more informed decisions about their mobility tools and the application of these tools to specific travel situations and environments.

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