Background and Purpose. We have developed a novel cane device to be used in conjunction with a treadmill-based virtual reality (VR) locomotor system. This proof-of-principle paper reports the rationale, instrumentation, feasibility, and clinical implications of the cane device, as well as preliminary results from persons with stroke and healthy older adults using the device.

Subjects. Five persons with stroke and 5 healthy older adults participated.

Methods. Average walking speeds with and without use of the cane are compared between the overground physical environment (PE) and a self-paced, treadmill-based virtual environment (VE). Additional gait parameters examined while walking with and without the cane in the VE are: (1) gait variability quantified as the coefficient of variation (% CV) for stride duration, and (2) step width. We also reported and discussed the vertical loading forces transmitted through the cane during self-paced treadmill walking in the VE.

Results. Results reveal that walking with the instrumented cane on a treadmill is feasible for use in both healthy and stroke populations. It is evident that people who normally walk unaided benefit more from the instrumented cane than people who normally walk unaided.

Discussion and Conclusion. This work represents the first instrumented cane for use with a treadmill-based locomotor system. The use of this assistive device would add to the ecological validity of such gait rehabilitation systems. It is expected that gait training with the instrumented cane can be carried over to overground walking, although further studies are warranted.

Key Words: Walking aid, Virtual environment, Stroke, Locomotor rehabilitation.

BACKGROUND AND PURPOSE

Walking aids, specifically canes, are frequently used in gait rehabilitation and are often prescribed as a long-term mobility aid for people with a wide range of musculoskeletal, neurological, and balance conditions. In both stroke and elderly populations, the frequency of cane use in everyday life is very high, either for all walking activities or solely for community (out-of-home) mobility. In frail elderly populations, canes were rated as the second most important assistive device overall, after eye glasses.1 There are 2 main substantiated reasons why many people depend on this simple aid for mobility. First, using a cane is known to improve confidence and reduce the anxiety associated with “fear of falling,” which is a very important consideration for both the elderly and stroke populations.2 Second, many elderly people, and even high-functioning ambulators poststroke, do not venture outdoors without a cane; they feel that the cane provides increased security and safety. This dependency may be more pronounced in areas where weather conditions (ie, high winds, snow, ice, etc) can promote even greater fear when ambulating outdoors. Second, ample evidence now exists to clearly establish the role that cane use can play in improving balance control and postural stability during stance and gait.3-14 Rehabilitation specialists—physical therapists more so than any other professionals—are in the position to offer these patients appropriate recommendations and training with walking aids. Furthermore, it is the responsibility of physical therapists to assure that the theoretical knowledge upon which they base their clinical decisions is based on current information and up-to-date evidence.

Literature Review

One of the main goals of rehabilitation in stroke and other populations is the restoration of independent gait, with or without the use of an assistive device. Evidence has shown that task-oriented interventions and intense task practice15 promote the reacquisition of motor skills, including gait. Although evidence-based stroke practice recommendations strongly support the use of treadmills for gait training16,17 due to the intense repetition of gait cycles that can be performed, many clinicians believe that gait practice overground is nevertheless necessary to assure the transition from treadmill walking to “real world” walking (with or without a cane).

The ability to generalize learning and transfer gait adaptations gained from treadmill training to overground walking has improved with the emergence of virtual reality (VR) technology. The increased visual (optic flow) and other sensory inputs now available can better simulate natural, true-to-life walking conditions. However, even with these advances, there remains an important dissimilarity between treadmill and overground gait training. In our clinical experience, the fixed bars on treadmills (either in front or to the side of the treadmill’s walking surface) provide stabilizing support very similar to the parallel bars used in many physical therapy departments. Parallel bars are often used for preparation of gait training and a variety of balance and gait exercises. However, many physical therapists will restrict gait training conducted in parallel bars and promote early overground training (with a walking aid and assistance as needed) with the rationale that the rigid bars provide too much balance support that does not challenge the postural control required to eventually walk.

Claire Perez, PT, BSc, MSc(c), and Joyce Fung, PT, PhD

An Instrumented Cane Devised for Gait Rehabilitation and Research

Claire Perez, PT, BSc, MSc(c), and Joyce Fung, PT, PhD

Claire Perez is an MSc candidate at the School of Physical and Occupational Therapy, McGill University, Montreal, Quebec, Canada; and a physiotherapist and research assistant at the Jewish Rehabilitation Hospital, Laval, Quebec, Canada.

Joyce Fung is an associate professor and William Dawson scholar at the School of Physical and Occupational Therapy, McGill University, Montreal, Quebec, Canada; and director of research, Feil and Oberfeld/CRIR Research Centre, Jewish Rehabilitation Hospital, 3205 Place Alton Goldbloom, Laval, Quebec, Canada, H7V 1R2 (joyce.fung@mcgill.ca). Please address all correspondence to Joyce Fung.

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with a walking device. The same rationale can be used to explain the potential problem of limited carry-over effects from treadmill to overground walking with an aid. In order to master the dynamic skill of cane walking, the skill itself (or a simulation equally challenging) must be practiced.

An often-reported clinical opinion held by some physical therapists working in stroke rehabilitation is that gait abnormalities and asymmetry might increase with cane use. Laufer,\(^9\) however, investigated the effects of walking aids on balance and gait patterns in hemiparetic (chronic) stroke survivors, and concluded that cane use does not cause greater weight-loading asymmetry even when balance is challenged. Moreover, the spatial gait characteristics (stride length and step length) were found to significantly increase while kinematic deviations were reduced on the paretic side, as compared to walking without the use of a cane. A recent study that examined the immediate effect of cane use in a subacute stroke population with existing gait asymmetry further established that temporal gait symmetry is significantly improved with a standard, single-point cane, but not with a 4-point (quad) cane.\(^14\) Additionally, cane use did not adversely affect trunk movements in people poststroke, as demonstrated by Tyson.\(^6\) Another recent study involving patients poststroke in the early phases of rehabilitation\(^12\) compared 3 different walking aids on walking capacity, temporal distance gait parameters, and patient satisfaction. The simple cane with an ergonomic handgrip was found to be the most efficient compared to 2 other commonly used walking aids during gait training (quad cane and Nordic Walking Stick). It also was most preferred by patients, which is an important consideration, especially when prescribing aids. The reality is that as many as 76% of people poststroke have been reported to use at least 1 gait aid\(^18\) and for most, that includes gait aids. The reality is that as many as 76% of people poststroke have been reported to use at least 1 gait aid.\(^18\) There is growing evidence to support that this latter function of canes, providing additional sensory and proprioceptive feedback, may play a particularly vital role in stabilizing gait in populations with general balance problems, including older adults and people with stroke. The sensory feedback related to body position may serve to compensate for sensorimotor impairments affecting balance control and help cane users reduce fall risk and achieve independent ambulation. Studies examining the forces exerted on canes in people with poststroke gait dysfunctions have demonstrated generally lower-peak vertical forces, as compared to people with musculoskeletal or orthopedic conditions where the reduction in limb loading is of primary concern.\(^7\) It is possible that people with balance problems (including elderly and stroke populations) use canes more for this attribute of facilitating postural control through increased somatosensory information, rather than as a means of physical support. Preliminary results from a current study on the effects of enhanced somatosensory input (from both haptic cues and cane use) on level and incline walking in people poststroke are pointing toward beneficial effects, including increased gait rhythmicity (decreased stride time variability) and gait speed, decreased step width, and improved center-of-mass (COM) control.\(^19\)\(^–\)\(^21\)

Over the past 2 decades, researchers and clinicians have explored the effect of using technology for stroke gait rehabilitation. An advanced system that combines the use of virtual environments (VEs) with a self-paced treadmill mounted on a 6-degree-of-movement motion platform has been developed and used for gait evaluation and retraining in people poststroke.\(^22\) The use of VE typically presents the user with opportunities to engage in environments which appear and feel similar to real-world situations and events. The use of VR technology to study and train both upper- and lower-extremity motor skills in people with stroke has been well documented and established.\(^23\) Virtual reality systems also are now more accessible in hospital and rehabilitation settings, making them more available for everyday clinical use. Despite the important and widespread use of canes, canes have not yet been incorporated into these new methods of gait training. The concept of creating a cane for use with a self-paced treadmill, although simple, adds to the ecological validity of a VR system and thus enhances the simulation of true-to-life walking activities. It is suggested that transfer of learning to overground walking with a cane may also be facilitated. The purpose of this paper is to present the development of this novel cane device and provide results from a pilot study investigating the cane’s feasibility.

**SUBJECTS**

Five people with stroke (age 65.2±5 years) and 5 healthy controls (67.6±6 years) participated in this study. The participants were part of the larger study examining the extent to which additional sources of sensory information affect gait performance during incline walking in people poststroke, as mentioned earlier.\(^19\)\(^–\)\(^21\) The additional sensory input was provided through contact cues at the finger-tick (haptic cues) or through the palm of the hand with use of a specifically designed instrumented cane presented in this paper.

**METHODS**

**Instrumentation and Measures**

An advanced locomotor system which combines the use of VR with a self-based treadmill and a motion platform, as previously documented,\(^22\) was used. This system is coupled with a 3D scene rear projected onto a large screen in front of the treadmill creating a VE. The Computer-Assisted Rehabilitation Environment (CAREN) software manufactured by Motek Medical BV\(^24\) controlled and synchronized the instantaneous treadmill speed with the VE scene progression and the platform movement.

The VE scenario designed for this project was that of a clearly delineated, 40-meters long outdoor walking path set amidst grass and trees. Kinematic data, sampled at 120 Hz, was gathered using a 6-camera Vicon MX motion analysis system manufactured by Oxford Metrics Group.\(^25\) Subjects wore reflective markers positioned on body landmarks according to Vicon’s Plug-in-Gait model. Prior to walking, the Activities-specific Balance Confidence (ABC) questionnaire was completed with subjects in an interview format. The ABC rates balance self-efficacy, reflecting the subject’s own perspective on his or her walking abilities, and is valid in a stroke population.\(^26\)

Three walking trials within the VE were analyzed; the first trial, or baseline trial, without cane use (NC1); the cane trial (which was randomly inserted within other walking conditions for another study\(^19\)\(^–\)\(^21\)); and the third, or last trial, without cane use (NC2). For 2 subjects, only the baseline trial was used (due to a technical problem in S3 and fatigue in S5). The gait parameters under study were speed, variability (coefficient of variation for stride duration [% CV]) and step width. The overground gait speed was measured with the 10-meter walk test, whereas gait speed
within the VE was calculated using the instantaneous speed output from the treadmill motor through the middle 20 meters of "steady-state" walking. Values were averaged over the 2 10-meter lengths for comparison with the overground measures. To calculate stride-to-stride variability and step width, the kinematic data was processed with a customized computer script in Matlab software, developed by MathWorks, to determine the gait events of initial foot contact and foot-off for each limb, based on the sagittal plane foot trajectory. Measures of gait variability have been found to be more sensitive than direct gait measures such as gait speed, and therefore provide more precise indices of walking performance. Less variability in a gait parameter such as stride duration would indicate a more rhythmic and stable gait pattern. It is suggested that measures of variability may also reflect qualitative aspects of gait otherwise overlooked by measuring gait speed alone. Stride duration was defined as the time taken between 2 consecutive initial foot contacts of the same limb (1 gait cycle). The % CV for stride duration, measured as the percent standard deviation over the mean, was compared between conditions (cane versus no cane) and between groups (stroke versus controls). Step width was defined as the distance (cm) between the left and right limb heel as measured by heel marker distance when in the double support phase of gait. Step width is often related to dynamic gait stability such that decreases in width represent better balance and improved postural control. The gait cycles occurring in the middle 20 meters of walking were retained for analysis.

Visual analog scales (VAS) were used to evaluate individual differences and were completed immediately following the experiment. Two parameters of interest were quantified: (1) the degree of ease (0/10) or difficulty (10/10) in using the cane; (2) the attention directed towards walking (0/10) or cane use (10/10).

**Treadmill cane device.** A typical single-point, adjustable aluminum cane with an offset foam handle was refurbished for use with the treadmill. The lower section of the cane was affixed with a ball joint with its center mounted onto the center of a tri-axial force transducer, produced by AMTI (series MC2.5-500). The ball joint permits the cane to be moved in 3 degrees-of-freedom, but constrained to a standard deviation of 30 degrees in both the sagittal and frontal planes. The combined cane tip-ball joint force transducer unit was then mounted onto a metal plate that was screwed on to either the left or right side of the treadmill, as needed (Figure 1). The upper-cane part with the handle could then be slipped over the lower unit and adjusted for cane height. Three additional holes were drilled into the upper-cane tube to accommodate the extra height of the force transducer (approximately 3 inches). The analog force data were sampled at 1200 Hz. The vertical force data were processed using a customized Matlab program. The values were expressed as a proportion of the body mass of the individual and then normalized to the gait cycle.

**Protocol**
All participants signed an informed consent form approved by the Montreal Centre for Interdisciplinary Research in Rehabilitation (CRIR) institutional ethics review board. The single experimental session began with an interview and clinical measures, including the 10-meter walk test with a cane (for those who used the aid in their everyday lives) and/or without the cane.

The reflective markers were attached and a safety harness was positioned on all subjects, which was then secured to a ceiling track during walking trials. Participants walked on a self-paced treadmill while viewing the VE scene projected in front as they walked a 40-meter level path. For added safety, a physical therapist stood nearby and supervised the subjects with stroke, as needed.

As noted, the participants were in control of their own walking speeds on the treadmill since they were tethered onto an electromotor with the digital output and its first-derivative servo-controlling the treadmill motor. They were instructed to walk at a comfortable pace. Each subject underwent a period of habituation that included walking on the self-paced treadmill on level, up, and down slope surfaces (5° slope change) with and without cane use, as well as adapting to the VE. The experimental protocol involved 3 walking surface conditions, including level, up slope, and down slope, along with 3 touch conditions, including no cane (NC), cane (C), and use of light touch (haptics). The presentation order of the walking conditions was randomized between 2 baseline trials (NC-level walking). The baselines were used in order to examine the effect of learning and adaptation to the system as well as to evaluate fatigue. Rests were provided as necessary during both the habituation and the experimental phases. For the purpose of this paper, only the experimental trials of level walking with and without the cane were analyzed.

**Results**
Participant characteristics and their overground gait speeds are described in the Table. The average chronicity of stroke was 5.1±2.1 years. Scores from the ABC questionnaire are also provided. For all subjects with stroke, the instrumented cane was held in the non-affected hand during treadmill walking.
whereas the controls were asked to choose their preferred hand for cane use (likely corresponding to their dominant hand).

As expected, gait speeds were generally lower in people with stroke, as compared to healthy older adults, regardless of environment (VE or physical environment [PE]). All subjects walked with a lower gait speed on the self-paced treadmill within the VE, as compared to overground walking within the PE. The mean reduction in gait speeds in the VE was greater for the subjects with stroke, as compared to controls. For both groups, the speed in the VE cane conditions was closer to the overground speed. The mean speed changes from overground walking in the PE to treadmill walking in the VE walking without the cane was a reduction of only 2% with the cane, as compared to 27% without. For controls, the reduction in speed ranged between 6% with the cane and 10% without the cane. The second baseline condition without cane use (NC2), when available, tended to be higher than the first (NC1). The mean gait speeds with and without cane use for both groups are provided in Figure 2. A mean increase of 20% in speed occurred when the subjects with stroke used the cane, while healthy controls demonstrated a mean change of 3%.

Figure 3 shows the gait speeds from 3 representative individuals; 2 subjects with stroke and 1 healthy control subject. The 2 subjects with stroke contrast between higher and lower functioning, based on their overground walking speeds. The stroke subjects, when using the instrumented cane, were able to closely match their PE walking speed when using the cane in the VE. The control subject appears to show greater difficulty in using the cane as reflected by the corresponding lower gait speed in the VE cane condition.

**Table. Subject Characteristics**

<table>
<thead>
<tr>
<th>Stroke Subjects</th>
<th>Age (years)</th>
<th>Gender</th>
<th>Lesion Side</th>
<th>Cane Use</th>
<th>OG Gait Speed (m/s)</th>
<th>Treadmill Cane side</th>
<th>ABC Score (%)</th>
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<tr>
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**Healthy Controls**

<table>
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<th></th>
<th>Age (years)</th>
<th>Gender</th>
<th>Lesion Side</th>
<th>Cane Use</th>
<th>OG Gait Speed (m/s)</th>
<th>Treadmill Cane side</th>
<th>ABC Score (%)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>68</td>
<td>M</td>
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<td>L</td>
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<table>
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<th></th>
<th>Age (years)</th>
<th>Gender</th>
<th>Lesion Side</th>
<th>Cane Use</th>
<th>OG Gait Speed (m/s)</th>
<th>Treadmill Cane side</th>
<th>ABC Score (%)</th>
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<tbody>
<tr>
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<td>2F</td>
<td>1.26</td>
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Abbreviation: m/s, meter per second.

**Figure 3. Individual Differences in Gait Speeds With and Without Cane Use**

Gait speeds (m/s) with and without cane use for 1 control and 2 stroke subjects are shown. The bar graphs represent speeds in the virtual environment (VE) and horizontal lines represent the overground gait speeds in the physical environment (PE). S2, who no longer uses a cane, responds more like a healthy non-cane user, C2 than to S5 who continues to require a cane.

Mean gait variability for the stroke and control group is shown in Figure 4. As expected, gait variability quantified as % CVs of stride duration was higher in the stroke group regardless of walking condition. All subjects in the stroke or control groups show a significant decrease in stride duration variability in both limbs when using the instrumented cane. The reduction in variability ranged between 16% to 18% for the subjects with stroke, and 5% to 15% for the healthy controls.

Step width for the stroke group was reduced by a mean of 9.9% when using the instrumented treadmill cane, as compared to the no-cane condition (Figure 5), with all subjects demonstrating decreased step width. In controls, although an overall mean reduc-
tion of 9.6% also occurred with cane use, the responses were more varied, and 2 subjects increased step width when using the cane.

As expected, the peak and mean loading forces applied to the cane were higher in the stroke group compared to controls (stroke: mean $F_z = 64.75 \pm 32.32 = 7.82\% \text{BW} \pm 3.39$; controls: mean $F_z = 23.54 \pm 14.01 = 3.1\% \text{BW} \pm 1.70$). Moreover, distinct differences were seen among the study subjects who normally used canes and those who did not. Figure 6 shows the cane forces calculated for the same 3 subjects as shown for gait speed (1 lower vs. 1 higher functioning subject with stroke and 1 control). The peak force exerted on the cane coincided with the stance phase of the more involved limb for the lower-functioning stroke individual who normally required a cane to walk, due to greater gait and balance dysfunction. The peak force and force pattern in the higher-functioning stroke individual, who did not use a cane, was more similar to that found in the control subject.

Subjectively, all participants found walking with the treadmill cane to be “easy” according to the VAS questions (with a rating [mean $\pm SD$] of 1.5/10.0 $\pm 1.1$ for stroke; 0.8/10.0 $\pm 0.4$ for controls). With regards to the focus of attention, all subjects perceived that more attention was directed towards walking than cane use, but interestingly, the perceived attention to cane use was higher in healthy controls ($2.5/10.0 \pm 2.1$) than stroke participants ($2.0/10.0 \pm 1.6$).

**DISCUSSION**

The purpose of this paper was to introduce a novel cane device specifically developed and designed for use with an existing treadmill-based immersive VE locomotor system. The overall concept was to add to the realism of the VE by making the walking activity more natural and similar to overground walking with a cane. The cane device, together with the motion platform, self-paced treadmill, and VE, created a more ecologically valid locomotion system that can be used as a tool for both clinical and research purposes.

Training gait with the cane device on a self-paced treadmill and immersed in a VE would allow patients to safely practice a variety of real-life walking skills (ie, crossing streets, maneuvering inclined surfaces, negotiating and avoiding obstacles, walking and shopping, etc). It would also allow therapists to have precise control over condition complexity and difficulty, which would be impossible overground with conventional therapy. The patients can walk with an aid similar to that which they would eventually use overground, such as a cane, and therefore training would specifically target skill acquisition. The balance control required for cane use as well as the motor control necessary to stabilize the cane would be promoted and practiced with greater repetition. Additionally, the sensorimotor integration involved in coordinating cane use with the gait cycle (ie, timing and loading patterns) could be developed more intrinsically during the intense training possible with treadmill walking. The instrumentation of the cane provides valuable information to the therapist concerning the amount of support a patient uses while walking. Based on this knowledge, clinicians could evaluate and train cane use more accurately. Precise recommendations with respect to the amount of force to apply on the cane could be made through real-time (immediate) feedback as the patient walks on the self-paced treadmill. This augmented feedback may facilitate more effective overground cane use. Patients may learn that only light support through the cane is required in order to improve gait performance and safety as well as enhance self-efficacy.

The improvements in gait (higher gait speeds, lower gait variability, and reduced step width) observed when the individuals with stroke walked with the instrumented cane on a treadmill as compared to walking without a cane, are consistent with gait changes seen during overground walking with a cane.7,8 Moreover, as expected, it appears that lower-functioning ambulators with stroke (or anyone who normally uses a cane) may benefit more from the instrumented cane than higher functioning individuals who do not need a cane. The timing of the peak vertical forces, coinciding with the stance phase for the affected limb, is consistent with other studies examining cane forces used in people with stroke.8 This further demonstrates the similarity in function between the instrumented cane on a self-paced treadmill and a regular cane for walking overground.

Using the instrumented cane was perceived to be easy for both stroke and control subjects. It is important to note that no explicit instructions for using the cane were provided to the subjects, and therefore the use was intuitive.
and the gait changes occurred naturally. An interesting observation is that the control subjects rated a relatively higher level of attention shifted to the cane as compared to the subjects with stroke. This might be due to the fact that cane walking was a novel task for the healthy controls, and as such, increased attention was necessary for skill acquisition, especially in what could be considered a dual-task activity.

CONCLUSION
This study demonstrates the successful development and feasibility of an instrumented cane to be used on a self-paced treadmill. To our knowledge, this is the first instrumented cane to be used in conjunction with a VR and treadmill-based locomotor system. It is suggested that treadmill gait training with the instrumented cane could transfer to overground walking with a cane. Further studies are required to explore this possibility and address clinical intervention issues related to using the instrumented treadmill cane.

REFERENCES