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Stepping over obstacles to improve walking in individuals with poststroke hemiplegia

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Abstract—For this study, we evaluated two training interventions for improving gait parameters in individuals with poststroke hemiplegia using a training methodology that required them to step over objects. Gait velocity, step length, ability to step over obstacles, and walking endurance were compared before and after 2 weeks of training and 2 weeks after cessation of training. Twenty subjects with poststroke hemiplegia completed six intervention sessions in which they were asked to step over either virtual objects while walking on a motorized treadmill or real foam objects on a 10 m walkway. With the virtual object training, if either foot collided with the virtual object, a tone sounded and a vibrotactile stimulus was applied to the colliding foot. All subjects tolerated the training sessions well, and no incidences of falling or undue cardiovascular responses occurred. The virtual obstacle training generated greater improvements in gait velocity compared with real training (20.5% vs. 12.2% improvement) during the fast walk test ($p < 0.01$). Improvements in gait velocity for both training methods were similar in the self-selected walk test (33.3% vs. 34.7% improvement). Overall, subjects showed clinically meaningful changes in gait velocity, stride length, walking endurance, and obstacle clearance capacity as a result of either training method. These changes persisted for 2 weeks posttraining. The inclusion of enhanced safety and visual augmentation may be responsible for the effectiveness of the virtual object intervention. These results demonstrate preliminary evidence for clinical effectiveness of obstacle training for improving gait velocity poststroke. In addition, these results provide evidence for enhanced clinical performance with virtual obstacle training.

Key words: accidental falls, biomechanics, computer-assisted therapy, exercise therapy, gait, stroke.

INTRODUCTION

Stroke is the number one neurologic cause of adult disability in the United States [1]. It is estimated that 600,000 Americans suffer a first stroke each year, and the nation's nearly 4 million stroke survivors are living with

Abbreviations: CVA = cerebrovascular accident, HIV = human immunodeficiency virus, MS = multiple sclerosis, OG = real obstacle training, SCI = spinal cord injury, SD = standard deviation, SS = self-selected pace, VA = Department of Veterans Affairs, VR = virtual obstacle training, VRSL = Virtual Reality Scripting Language.

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the consequences [2]. Stroke survivors constitute a substantial portion of the disabled veteran population. With the aging of this population, the number of veterans with these conditions is expected to increase. Many of these veterans have walking problems and are particularly susceptible to falls and subsequent injury.

Due to the sudden and catastrophic nature of the brain involvement, stroke patients and their families are faced with the challenges of dramatically altered lifestyles compromised by the loss of functional independence, especially decreases in mobility and the ability to perform activities of daily living. Although 60 percent of stroke survivors regain walking independence after 3 months, many have continuing problems with mobility due to impaired balance, motor weakness [3], and decreased walking velocities [4]. According to a recent study [5], 85 percent of these individuals failed to reach age-specific norms for gait speed even 3 months after the incident.

Stroke survivors also have an increased risk for falls and subsequent injuries due to their locomotor disabilities, including impaired balance, decreased stride length, decreased walking speed, compromised ability to step over objects, and decreased endurance [6,7]. These locomotor disabilities result in an inability to respond quickly and appropriately to challenges within their environment such as stairs, inclines, and uneven surfaces. Current training methods to improve walking patterns of individuals with poststroke hemiplegia during rehabilitation involve a therapist giving verbal cues and manual support during overground walking and using equipment such as parallel bars, mirrors, and stairs. Long-term and ongoing access to individualized walking therapy is seldom provided or covered by insurance.

We used stepping over obstacles as an alternative training technique to improve walking in individuals with poststroke hemiplegia. We hypothesized that the obstacle training would lead to improvements in the various measures of walking ability. We further hypothesized that a computer-based virtual object technique would produce better results than a non-computer-based technique.

METHODS

This study tested the ability to improve walking by training individuals with poststroke hemiplegia to step over obstacles, an easily understood goal-oriented task. The subjects were required to lift their legs high enough and far enough to clear the front and back edges of the obstacle. Changing the height and length of the obstacle altered the task's difficulty. (The convention used in this study refers to the size of obstacle along the direction of walking as its "length.") The research protocol consisted of several elements: subject recruitment, cognitive screening, pretraining evaluation, training intervention, posttraining evaluation, and follow-up evaluation.

Subjects

Subjects were recruited from the local community Peninsula Stroke Association meetings, by advertisements, by word-of-mouth, and through an announcement on the Palo Alto VA Rehabilitation Research and Development Center's website (http://guide.stanford.edu). Individuals were screened on the telephone to determine if they met the inclusion/exclusion requirements for participation in the study. Subjects were included in the study if they met certain criteria described here. Criteria 1 to 3 were obtained from the telephone screening. Individuals who met the first three criteria were evaluated by a research physical therapist for criteria 4 to 6.

Inclusion criteria were

1. Had a cerebrovascular accident (CVA) more than 6 months ago.
2. Had a diagnosis of hemiplegia secondary to a single documented lesion.
3. Could walk independently or with a guard (with or without an assistive device).
4. Had an asymmetric gait pattern (temporal and/or spatial).
5. Demonstrated a short step-length with either step defined as less than the 95th percentile of normal step length.
6. Scored in the "average" to "minimally impaired" range in all Cognistat™ categories, unless performance was markedly limited by aphasia, making assessment of cognition difficult.

Exclusion criteria were

1. Had neurologic diagnoses of spinal cord injury (SCI), multiple sclerosis (MS), or brainstem lesion.
2. Had any progressive, critical, or long-term illness (e.g., cancer, human immunodeficiency virus [HIV], Parkinson's Disease).
3. Required oxygen during ambulation.

4. Had an unstable cardiovascular, orthopedic, musculoskeletal, or neurological condition that would preclude exercise in short duration, low-workload trials.
5. Had an unstable medical condition that is not controlled by medication, e.g., hypertension, diabetes, seizures, dizziness or vertigo, peripheral vascular disease, disabling arthritis, or neck or back pain, that limits activities.
6. Were blind or experienced a visual field deficit.
7. Had an amputation of either leg.
8. Had a joint replacement in either leg or hip.
9. Demonstrated an inability to follow instructions.
10. Had an intracranial neoplasm, an aneurysm, or brain tumor surgery.

Informed Consent

Informed consent was obtained from each subject as approved by the Institutional Review Board of the Stanford University Medical School.

Cognitive Screening

The Cognistat™ Test was designed to rapidly assess intellectual functioning in five major ability areas: language, constructional ability, memory, calculation skills, and reasoning/judgment. The language section has four separate subsections: spontaneous speech, comprehension, repetition, and naming. This standardized test was administered by a research physical therapist to screen the cognitive ability of potential subjects [8].

Evaluations

Evaluations consisted of a Balance Test, Walking Test, Obstacle Test, and 6-Minute Walk. They were performed immediately prior to training, upon completion of 2 weeks of training, and 2 weeks after cessation of training. The collected data provided information regarding the effect and duration of the training intervention on improvements in balance, walking speed, stride length, ability to clear obstacles, and walking endurance.

Balance Test

In this study, a simple balance test (**Table 1**) consisting of seven tasks adapted from the Performance-Oriented Assessment of Mobility [9] and the Physical Performance Test [10] was performed during each evaluation. The tasks were natural stance, natural stance with eyes closed, on toes, tandem stance, tandem stance with eyes closed, left leg only, and right leg only. Two points were given for successful completion of each task, one point for adaptive completion, and zero points for unsuccessful completion.

Walking Test

Using a Stride Analyzer gait analysis system (B&L Engineering), we measured the spatio-temporal variables of gait (walking velocity, cadence, and stride length) as subjects walked at two speeds: self-selected (SS) pace and as fast as possible (fast). During the walking test, the subjects wore “booties” with thumbtacks protruding from the heel. As they walked over the 6-meter papered walkway, the tacks pierced the paper on each heel strike. Measurements of each footfall’s stride-by-stride step distances were made to determine gait asymmetry, data that the Stride Analyzer could not measure. The paper-based distance data were also used to cross-check the Stride Analyzer. Six tests were performed: three each at the self-selected and fast speeds. A therapist guarded the subject, and the entire session was videotaped.

Table 1.
Balance test.

Balance Task	Normal 2 Points	Adaptive 1 Point	Abnormal 0 Points
Natural Stance	Steady 10 s	—	Unsteady
Natural Stance, Eyes Closed	Steady 10 s	—	Unsteady
On Toes	Maintains 10 s	Unsteady	Maintains <10 s
Tandem Stance	Steady 5 s	Sways, staggers, moves	Maintains <5 s
Tandem Stance, Eyes Closed	Steady 5 s	Sways, staggers, moves	Maintains <5 s
Left Leg Only	Maintains 5 s	—	Maintains <5 s
Right Leg Only	Maintains 5 s	—	Maintains <5 s

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Obstacle Test

Obstacle clearance performance was measured as subjects attempted to step over foam obstacles ranging from 2×2 in. to a height and length determined by their leg length. Maximum obstacle height was equal to the height to the subjects' inferior border of the patella while maximum length was height to the subjects' trochanter minus one-half the maximum obstacle height. Subjects were given three chances to clear each obstacle without touching it or circumducting it. The longest obstacle successfully negotiated at each height was recorded.

6-Minute Walk

In this simple measure of walking endurance, subjects were instructed to cover as much distance as possible in 6 minutes [9]. The test was performed in a long straight hallway marked at 10-foot intervals. After 100 feet, the subject turned around and continued walking until 6 minutes had elapsed or the subject became too tired to continue.

Training Interventions

Subjects were randomized into one of two training methods: real or virtual. In both training interventions, the subject was instructed to step over 10 identical stationary obstacles of a selected height and length. The physical therapist guarded subjects and provided equal stepping suggestions and encouragement during both interventions. Twelve trials over these ten obstacles constituted one session. The number of obstacles was the same for both interventions. The small number of steps taken during these interventions is in distinct contrast to the highly repetitive body weight-supported treadmill-training paradigm.

The intervention consisted of six sessions of approximately 1-hour duration over 2 weeks. Blood pressure was taken before and after each session. After each run, the subject's heart rate, oxygen saturation, and perceived level of exertion were recorded. The subjects' heart rates and oxygen saturation were measured with an O_2 saturation monitor while the perceived level of exertion was that reported by the subject using the Borg Scale. The entire session was videotaped. If a subject cleared 80 percent of the obstacles during a session, the next larger obstacle was employed for the subsequent session.

In the real object training method, subjects wore a gait-belt and stepped over foam obstacles in a hallway. We spaced the obstacles at intervals of 15 to 22 in. This spacing was calculated from the average self-selected stride length during the pretraining evaluation for each subject and was maintained throughout the training program. The session was videotaped and reviewed for collisions with the obstacles after the session was completed.

In the virtual object training method, subjects walked on a motorized treadmill at a self-selected walking speed and were held safely in place using an overhead harness. It is important to note that although the subject held onto the treadmill's handrails, he/she supported his/her entire weight on the treadmill. The harness prevented falls.

A color video camera was directed at the subject's legs from the side **(Figure 1).** The subject wore a Virtual Research V6 head-mounted display to view the real-time image produced by this camera. Despite the "total immersion" nature of the images in the head-mounted display,

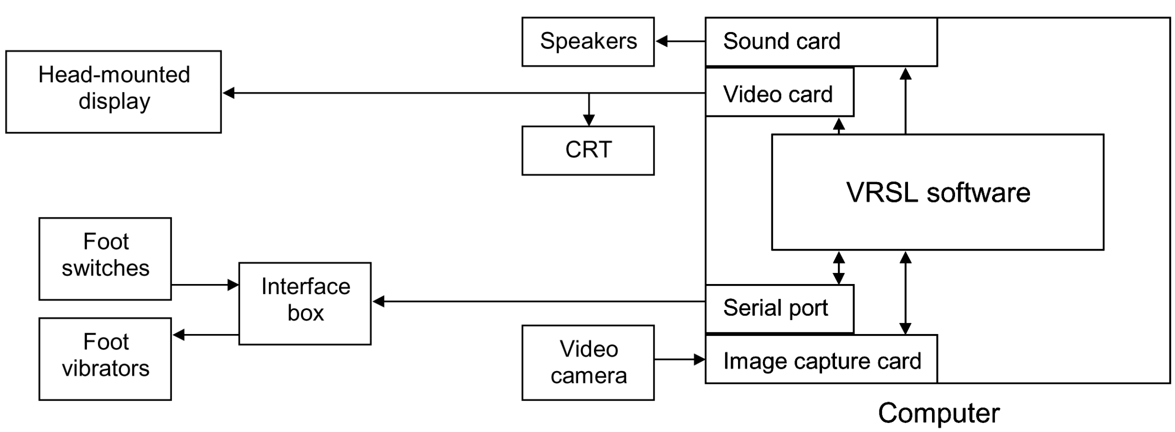

Figure 1.
An overview of system block diagram used for virtual object training method. VRSL = virtual reality scripting language.

no dizziness was reported, even with one subject who previously experienced episodes of claustrophobia at home. Subjects stated that the lateral view of the legs provided a very useful visual cue for stepping over objects. This perspective allowed subjects to observe the position of their feet, monitor their knee flexion, time their toe-off, and control their stepping height and length. A Pentium III computer system ran a software application program written in VRSL (Virtual Reality Scripting Language by Vivid Group, Toronto, ON). Using a commercial video card, the program captured the video images of the subjects' feet from the video camera and introduced a stationary image of the obstacle, which was a rectangular object of a selected height and length. The combined image was displayed on the head-mounted display for the subject and on a computer monitor for the therapist.

While walking on the treadmill, the subject was instructed to step over the virtual obstacle with each foot for a total of 10 steps. (During training interventions, the treadmill was set to a speed with which the subjects felt comfortable. This speed remained constant throughout the study for the particular subject.) The computer system detected any intersection of the users' feet with the obstacles **(Figure 2).** A collision by the toe on the front edge of the object indicated that the subject had not lifted the foot high enough, while a collision with the heel on the top of the object indicated that the subject had not stepped far enough.

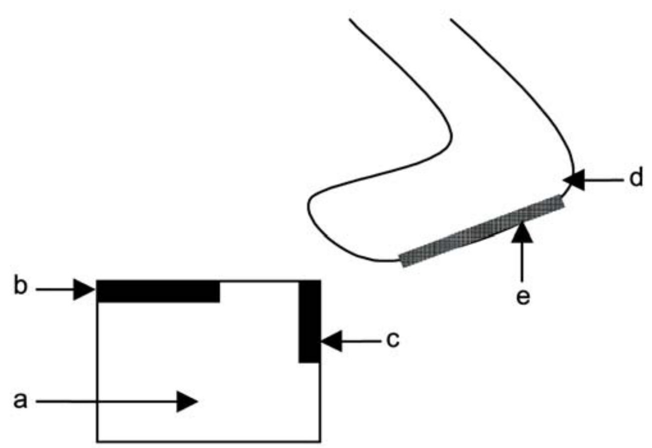

Figure 2.
For the virtual object training method, the computer system detected any intersection of the users' feet with the obstacles. **a** = computer-generated obstacle, **b** = rear sensitive area of computer-generated obstacle, **c** = front sensitive area of computer-generated obstacle, **d** = reflective tape on bootie, and **e =** foot switch between shoe and bootie.

A flat foot switch was placed in the bottom of commercial rain shoe coverings, the "bootie." This combination was worn over the subjects' own shoes. The foot switches identified which foot was off the ground. Vibrotactile feedback produced by pager vibrator units was directed to the heel or toe of the foot that caused the collision. A short tonal sound provided an audio feedback of any collision. The computer system monitored the subject's progress during the training sessions, keeping track of the steps and number of collisions that occurred. The data collection started when the treadmill came up to the desired walking speeds, which occurred after approximately two to three steps. The resultant data file was read into an Excel template to total the collision information.

The visual, vibrotactile, and auditory feedback in the virtual object training method provided multiple ways of informing the subject of a collision. The lateral view of the legs gave subjects useful visual cues for stepping over the computer-generated virtual objects. They were able to observe the position of their feet in relation to the obstacle to determine when best to lift their feet, how high and how far to step, and how much ankle and knee flexion to produce to successfully clear the obstacle. The hip flexion, although not visualized in the head-mounted display, does play a role in the overall movement.

Data Analysis

An unpaired *t*-test was used to test the hypothesis that percentage improvements in outcome measures were observed with the virtual group compared to the real object group. A *p*-value of 0.05 or less was used to demonstrate significant differences. A paired *t*-test was used to test the hypothesis that, within each intervention group, percent improvements in outcome measures were significantly greater than zero with a *p*-value of 0.05 as the test for significance.

RESULTS

The 20 subjects (10 in the real object group and 10 in the virtual object group) in both training groups exhibited a wide range of pretraining capabilities and posttraining performances in the major outcome measures. The demographic characteristics of the overall subject population were an average age of 61.5 years, an average of 3.7 years duration poststroke, 8 female and 13 male, and 10 with right-side and 11 with left-side paretic weakness

(**Tables 2** and **3**). It is important to note that both training methods proved to be safe because no falls occurred during the training.

Figure 3 illustrates the percentage of improvement for each of the two training interventions for ten outcome measures. Percentage of improvement is defined as 100X (posttraining performance)/(pretraining performance). Improvements occurred in every outcome measure except one (overground step length of the nonparetic leg during fast pace). The group receiving the virtual object intervention training achieved significantly faster walking speed (**Table 4**) and longer stride length for the fast-pace walking evaluation tests. The virtual object protocol results showed greater improvements when compared to the real object protocol in 7 of the 10 outcome measures. A slight but insignificant change in cadence was

Table 2.
Subject characteristics.

Subject	Age (yr)	Gender	Time Since Stroke (yr)	Left/Right Paretic	Intervention
A	69.0	F	3.1	R	OG
B	48.8	M	2.5	L	VR
C	50.4	M	3.5	L	VR
D	54.2	M	7.4	R	VR
E	51.0	F	8.7	R	VR
F	55.5	M	3.5	R	OG
G	59.8	F	2.7	L	VR
H	70.4	F	8.4	R	OG
I	54.4	F	1.6	L	OG
J	67.0	F	3.9	L	VR
K	66.7	M	2.6	L	VR
L	79.4	M	1.8	L	VR
M	79.6	M	1.4	R	OG
N	41.6	F	3.7	R	VR
O	63.4	F	2.4	L	VR
P	56.3	M	N/A	L	OG
Q	58.3	M	1.7	L	OG
R	68.9	M	4.8	R	OG
S	59.3	M	1.3	R	OG
T	60.0	M	6.4	L	OG
Average (SD)	60.7 (2.3)	8 F (12 M)	3.8 (2.2)	10 R (10 L)	10 OG (10 VR)

SD = standard deviation
R = right leg
L = left leg
M = male
F = female
OG = real obstacle training
VR = virtual obstacle training
N/A = not applicable

Table 3.
Subject characteristics.

Training Group*	Age	Gender	Time	L/R
OG (SD)	63.2 (8.3)	3 F (7 M)	3.6 (2.6)	6 R (4 L)
VR (SD)	58.2 (11.2)	5 F (5 M)	3.9 (2.3)	4 R (6 L)

*10 Subjects in each group
SD = standard deviation
OG = real obstacle training
VR = virtual obstacle training
L = left leg
R = right leg
M = male

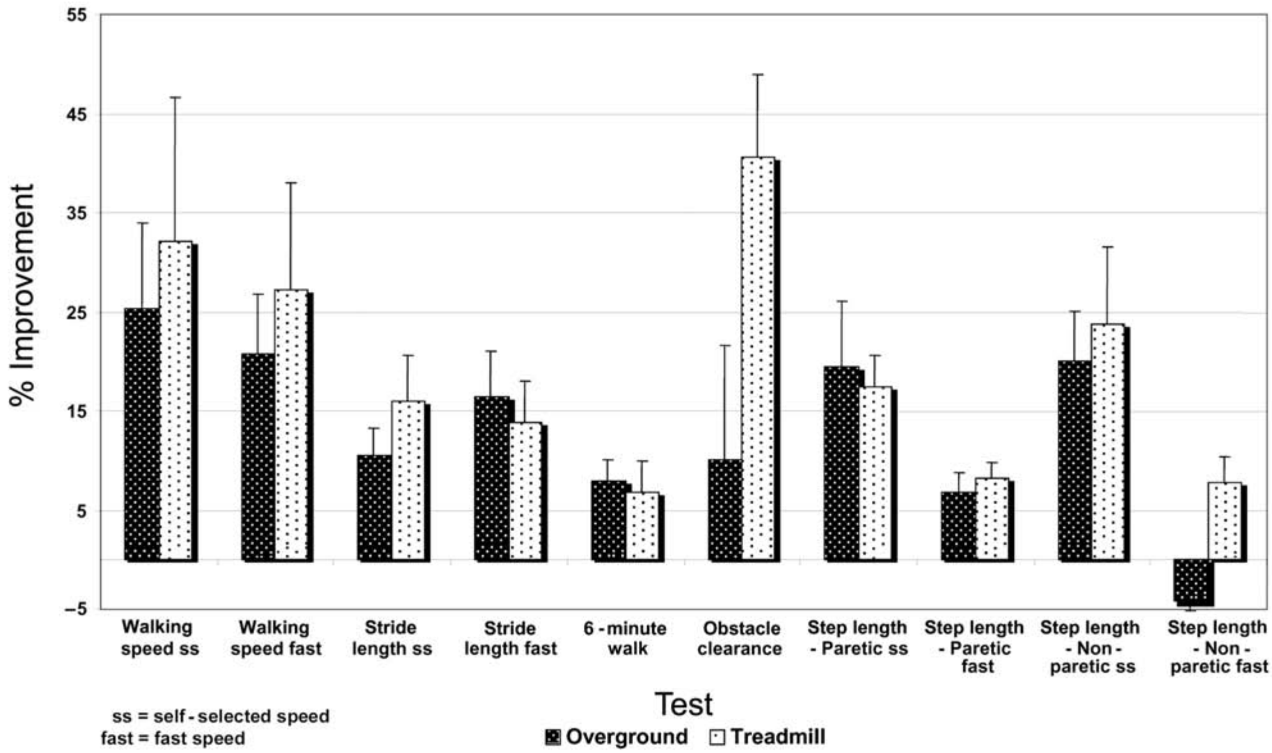

Figure 3.
Ten outcome measures were used to determine percentage of improvement for each of two training interventions.

observed. The subjects did not take more steps per trial. Instead, they took longer steps, which resulted in a greater walking speed.

Figure 4 shows the percentage of retention of the two training interventions for 10 outcome measures at 2 weeks posttraining. It is defined as 100X (follow-up training performance)/(posttraining performance). A value greater than 100 percent indicates that the performance measured 2 weeks after the conclusion of training was greater than the performance measured immediately after the completion of training (e.g., additional improvement occurred after completion of the training). Overall, subjects showed greater than 95 percent retention in all key gait parameters at the 2-week follow-up period. Some measures (i.e., step length of the nonparetic leg, fast) showed continued improvement at the 2-week follow-up.

DISCUSSION

Both the real and virtual object training techniques in this study showed improvements in walking for individuals with poststroke hemiplegia well after the onset of their stroke (average of 3.7 years in this study). The virtual object training technique produced a real-time and useful visual stimulus for stepping and provided a unique perspective unavailable to a subject looking down at his/her feet. The treadmill and harness system offered a safe environment in which to respond to therapist's suggestions and try new strategies of moving and stepping. The therapist could simultaneously view (via the computer monitor) the same image as the subject to observe the subject's response to movement suggestions. The real-time nature of all feedback modalities (visual, audio, and vibrotactile) is an important element in the VR training intervention. The visual feedback when successfully negotiating with a virtual obstacle reinforced the subject's positive efforts. The enhanced feedback may indeed be the dominant factor leading to the higher levels of walking improvement achieved by subjects in the virtual object group.

The computer added the capability to fully document and score each session, use objects of standardized size and placement, and easily change the height and width of the object as the subject improved.

Age cannot be considered a major contributor to the outcomes of our study because the two groups were

Table 4.
Pre- and posttraining walking speeds for all subjects in OG and VR groups. Four subjects from each group showed walking speed improvements that exceeded 0.17 m/s, the lower limit of measurement error in stroke patients reported by Goldie [4].

Subject	Group	Prevelocity (m/min)	Postvelocity (m/min)	% Improvement	Gain (m/s)
305	OG	39.5	34.5	–12.6	–0.08
309	OG	52.2	80.3	53.9	0.47
312	OG	41.8	63.2	51.1	0.36
313	OG	27.9	43.6	56.3	0.26
317	OG	21.6	31.2	44.4	0.16
322	OG	30.6	36.4	18.8	0.10
323	OG	35.7	47.6	33.2	0.20
324	OG	43.0	41.0	–4.6	–0.03
325	OG	23.2	26.4	13.8	0.05
326	OG	30.0	30.5	1.5	0.01
303	VR	22.2	22.8	2.6	0.01
304	VR	15.4	23.4	51.6	0.13
306	VR	46.0	65.0	41.4	0.32
307	VR	37.6	57.5	52.8	0.33
311	VR	45.4	62.1	36.8	0.28
314	VR	18.4	20.6	12.0	0.04
315	VR	14.5	20.0	37.9	0.09
316	VR	33.7	26.7	–20.8	–0.12
319	VR	49.2	51.8	5.4	0.04
320	VR	31.8	64.2	101.7	0.54

virtually identical in age. Although the average ages of each group differed by 5 years, the variability associated with the group average made the two groups statistically equal. Also, there are no studies that support a difference in an effect of gait training between subjects who are separated in age by 5 years. Typical studies report differences between younger (18–50 years) and older (greater than 60 years) subjects [10].

The results of the study suggest that virtual objects are just as effective as real objects in shaping the stepping characteristics of individuals with poststroke hemiplegia. However, there are several alternative explanations for the results. One possible explanation for improvement may be that the treadmill training can induce longer stepping without the use of virtual objects. Several studies demonstrate improved stepping with treadmill training [11–14]. However, the intensity of the treadmill training was low because we asked subjects to take a total of 10 steps per trial.

Therefore, if treadmill training played a role in the gains that we have reported, then the virtual objects possibly enhanced the gains since very few steps were practiced on the treadmill. An alternate explanation for our results may be that the harness provided an extra measure of safety to allow subjects to focus more on improving their gait. One further caveat to the interpretation of these results is the extra attention and excitement that was expressed by the subjects engaged with the virtual objects. A placebo effect may have been caused by the impressive setup of technological devices that subjects were involved with during the virtual object intervention. Further studies can be designed to account for these additional factors that can impact improvements in walking.

Improved walking mechanics will decrease the energy needed to walk and reduce injuries due to gait

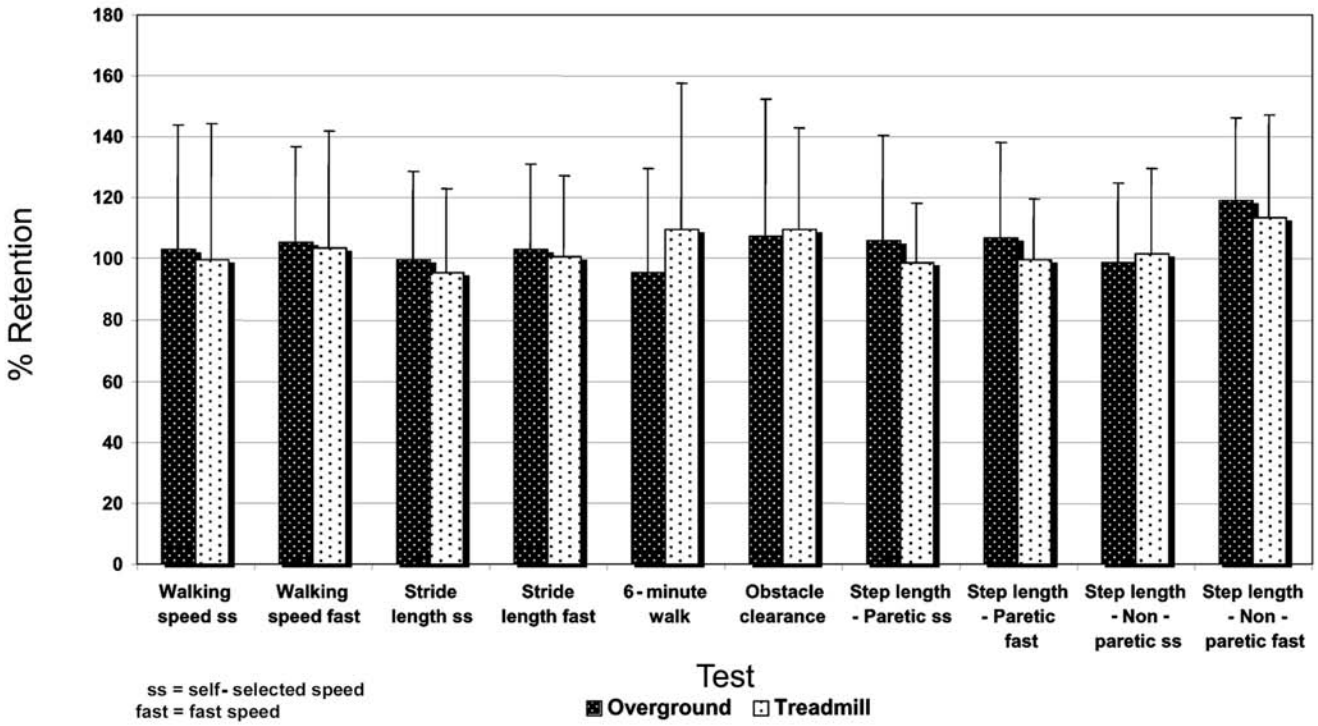

Figure 4.
Subjects showed greater than 95% retention in all key gait parameters.

abnormalities such as hyperextension at the knee. These improvements in walking will also enhance the ability of persons with stroke to better negotiate real-world overground environments (steps, obstacles, and uneven surfaces) and to walk independently and confidently. Training techniques to improve walking can lead to functional mobility gains and increased options for activities of daily living. In addition, improvement in gait, especially walking speed, is an indicator for reduced risk of falls and subsequent injury [15]. Improving walking could also mitigate compensatory strategies that may generate overuse injuries in the nonparetic leg, resulting in an increased risk for falling [16,17]. Decreasing the training time and also preventing falls will also reduce health costs. Most importantly, patients work with a therapist to safely practice new movement strategies to improve their walking ability, a prerequisite for returning to the workforce and regaining the ability to perform routine activities necessary for an independent lifestyle. The ability to walk safely and at a functional speed will enhance the quality of life by promoting increased involvement with family and community events.

However, the small number of subjects in this study and their wide range of initial ability and posttraining performance make it difficult to conclude that the virtual object training protocol was significantly better than the real object method in all the outcome measures. The limited number of training sessions and the scheduling of the evaluation sessions were unable to reveal plateaus in improvements. A proposed future study will include more training and evaluation sessions and will enroll sufficient subjects to determine the optimal training duration and identify the best training technique. The long-term goal of this follow-up work is to investigate various training methods of improving walking characteristics in individuals with poststroke hemiplegia. These will include visualization, traditional training, treadmill training, and the use of virtual reality techniques. The effectiveness and durability of these methods in increasing stride length, walking speed, balance, ability to step over obstacles, walking endurance, and quality of life will be measured and compared. In this new study the number of training interventions will be doubled to 12 over 4 weeks and additional outcome measures will be administered. The longer training period and the evaluation session performed at the midpoint of training will uncover additional gains beyond 2 weeks and identify a possible plateau in improvements. Collaborations for placement of the virtual object training systems in hospitals and clinics are being pursued. Follow-up research might include other subject populations such as traumatic brain injury, Parkinson's Disease, and incomplete SCI.

CONCLUSION

This study showed that training individuals with poststroke hemiplegia to step over obstacles produced improvements in their gait parameters, the ability to step over objects, and walking endurance. While both training methods were effective in improving gait parameters, the virtual object training technique produced more significant improvements, specifically during fast-speed walking.

A Report of Invention has been submitted to the VA Technology Transfer Program Office. A search for potential commercial manufacturers for the treadmill training system is ongoing.

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