Stroke
JOURNAL OF THE AMERICAN HEART ASSOCIATION

American Stroke Association
A Division of American Heart Association

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*Stroke* 2009;40;169-174; originally published online Nov 6, 2008;
DOI: 10.1161/STROKEAHA.108.516328
Stroke is published by the American Heart Association. 7272 Greenville Avenue, Dallas, TX 72514
Print ISSN: 0039-2499. Online ISSN: 1524-4628

# Effects of Training With a Robot-Virtual Reality System Compared With a Robot Alone on the Gait of Individuals After Stroke

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***Background and Purpose***—Training of the lower extremity (LE) using a robot coupled with virtual environments has shown to transfer to improved overground locomotion. The purpose of this study was to determine whether the transfer of training of LE movements to locomotion was greater using a virtual environment coupled with a robot or with the robot alone.

***Methods***—A single, blind, randomized clinical trial was conducted. Eighteen individuals poststroke participated in a 4-week training protocol. One group trained with the robot virtual reality (VR) system and the other group trained with the robot alone. Outcome measures were temporal features of gait measured in a laboratory setting and the community.

***Results***—Greater changes in velocity and distance walked were demonstrated for the group trained with the robotic device coupled with the VR than training with the robot alone. Similarly, significantly greater improvements in the distance walked and number of steps taken in the community were measured for the group that trained with robot coupled with the VR. These differences were maintained at 3 months' follow-up.

***Conclusions***—The study is the first to demonstrate that LE training of individuals with chronic hemiparesis using a robotic device coupled with VR improved walking ability in the laboratory and the community better than robot training alone. **(*Stroke*. 2008;40:169-174.)**

**Key Words:** community ambulation ■ gait ■ robotics ■ stroke ■ virtual reality

Stroke is considered to be the leading cause of adult neurological disability.[1] Walking impairments have been considered one of the most devastating disabilities of poststroke hemiparesis,[2] with only limited recovery,[2,3] because individuals are often discharged into their communities with residual impairments and disabilities.[4] Given their residual deficits these individuals may limit their mobility for safety reasons and consequently not accomplish community ambulation.[5] Therefore, improving walking for individuals after stroke remains a major component of poststroke rehabilitation. In fact restoration of walking was identified by individuals after stroke as 1 of their most important rehabilitation goals.[6,7] The standard of care for rehabilitation of ambulation includes task-specific training, body weight-supported treadmill training (BWSTT), and pregait activities.[8,9] These techniques are being complemented by emerging approaches to rehabilitate walking of individuals after stroke that include innovative technology and motor imagery.[10]

Innovations in technology applied to stroke rehabilitation include robotics and virtual reality (VR). The impetus for using such technology for stroke rehabilitation is their ability to increase motivation, be adaptable, collect data, maintain patient safety, and promote intensive individualized repetitive practice.[11,12] Robotics and VR devices enable the creation of interventions in which the duration, intensity, and feedback can be manipulated and enhanced to create the most appropriate exercise paradigm for the individual. These characteristics of training were reported to be closely related to recovery, reorganization, and cortical plasticity after stroke.[13–15]

Training using VR and robotic therapy have demonstrated improvements in both upper and lower extremity function after intensive treatment in both chronic and subacute populations.[11,15,16] Studies that focused on enabling walking using VR have been reviewed elsewhere.[16] Generally, they reported improvements in gait speed, stair climbing abilities, and walking distance as well as leg muscle activity, balance, and increased symmetry during gait after training.[16–20]

To date, there has been limited information about on long-term effects of training gait using robotics and VR and how it transfers to the home and community. In addition, there are no reports parsing the effects of a robot and the virtual environment. The purpose of this investigation was to determine if training with a robotic VR system produced

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Received January 30, 2008; final revision received June 5, 2008; accepted June 6, 2008.

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*Stroke* **is available at http://stroke.ahajournals.org** **DOI: 10.1161/STROKEAHA.108.516328**

**Table 1. Subject Characteristics**

| | Robotic VR Group, N=9 | Robotic Group, N=9 | *P* |
|---|---|---|---|
| Age, yr | 61.8±9.94 (41–75) | 61±8.32 (45–71) | 0.85 |
| Gender, M/F | 7/2 | 8/1 | 0.74 |
| Affected side, left/right | 6/3 | 4/5 | 0.34 |
| Time since onset, mon | 37.7±25 (12.8–83) | 58.2±26.3 (14.3–84.6) | 0.09 |
| Use of orthotic device, AFO | 5/9 | 7/9 | 0.15 |
| Initial LE FM score, 34 | 24±3.4 (19–28) | 22±4.5 (15–28) | 0.27 |
| Initial Berg Balance Scale, 56 | 48±7.8 (31–54) | 46±7.6 (37–55) | 0.59 |
| Initial walking speed, m/sec | 0.65±0.25 (0.18–1.08) | 0.67±0.28 (0.13–1.1) | 0.59 |

Mean, SD, and range provided. Statistics calculated using *t* test and $\chi^2$.
AFO indicates ankle foot orthosis; LE FM, lower extremity Fugl-Meyer.

greater transfer of training to overground walking and improved distance than the use of a robot alone. Specifically, we wanted to evaluate the training effect of each protocol and the retention at 3 months after training in a laboratory setting and to compare it to field measures taken in the community.

## Subjects and Method

### Participants

Fifteen men and 3 women with chronic hemiparesis after stroke were enrolled in this study. They exhibited residual gait deficits but had partial antigravity dorsiflexion and were able to walk 50 feet without the assistance of a person. None of them had motion sickness or was receiving concurrent therapy during the study. Subject characteristics are presented in Table 1. All subjects had sufficient communicative and cognitive abilities to participate and gave informed consent before the beginning of the study.

### Design

A single-blind, randomized, control study with a 2-factorial repeated measures design was used. Subjects were tested before and after they participated in a 4-week training program by a blinded assessor unaware of group allocation. Follow-up testing occurred at 3 months.

Clinical outcome measures included gait speed over a 7-meter walkway and the 6-minute walk test. Data on home and community walking activity were collected during a 1-week period before training and again 1 week after training, using the Patient Activity Monitor (PAM; Ossur). The PAM is a small accelerometer based monitoring device that is worn around the subject's ankle and is able to collect the following data: number of steps per day, average daily distance walked, speed, cadence, walking strides, maximum walking speed, longest consecutive locomotion period in minutes, and the longest consecutive distance traveled.[21] The Lower Extremity Fugl-Meyer and Berg Balance Scale were used as impairment and activity level measures to describe the subjects.

### Intervention

Subjects trained on the Rutgers Ankle Rehabilitation System, a 6-degree of freedom Stewart platform force-feedback system that allows individuals to exercise the lower extremity by navigating through a virtual environment that is displayed on a desktop computer. The development and testing of the device was reported elsewhere.[17,22,23]

Training was performed 3 times per week for 4 weeks for ≈1 hour each visit. Subjects trained in a seated position facing a computer monitor. The lower extremity was positioned with 90 deg of hip and knee flexion (Figure 1). Subjects moved the ankle into dorsiflexion, plantar flexion, inversion, eversion, and a combination of these movements. Force, speed, and excursion baseline performance were measured by the robot at the beginning of each session and were used as a reference for the exercise protocol. Exercises performed by each group were comparable and consisted of warm-up, endurance, speed, strengthening and coordination exercises, and emphasized the direction of movement and timing of segmental motion. Training intensity and progression of the protocol, designed based on previous studies[17,19,24] were adjusted for individual subjects based on their observed performance (relative to accuracy) and reported fatigue. The same physical therapist assisted the training of both groups.

Subjects in the robot VR group executed the exercises by using the foot movements to navigate a plane or a boat through a virtual environment that contained a series of targets. The position and timing of the targets were manipulated to insure training included discrete and combined ankle movements. Subjects who trained with the robot device alone received the same exercises as the robot VR group but without the virtual environment. The computer screen was occluded to block visual and auditory feedback. High-level haptic feedback synchronized with the simulation was turned off; however, low-level force feedback was provided by the robot.[22] Subjects in the robot alone group were instructed by a therapist on what direction to move their foot and were paced by a metronome cueing them to

**Figure 1.** Robotic VR device.

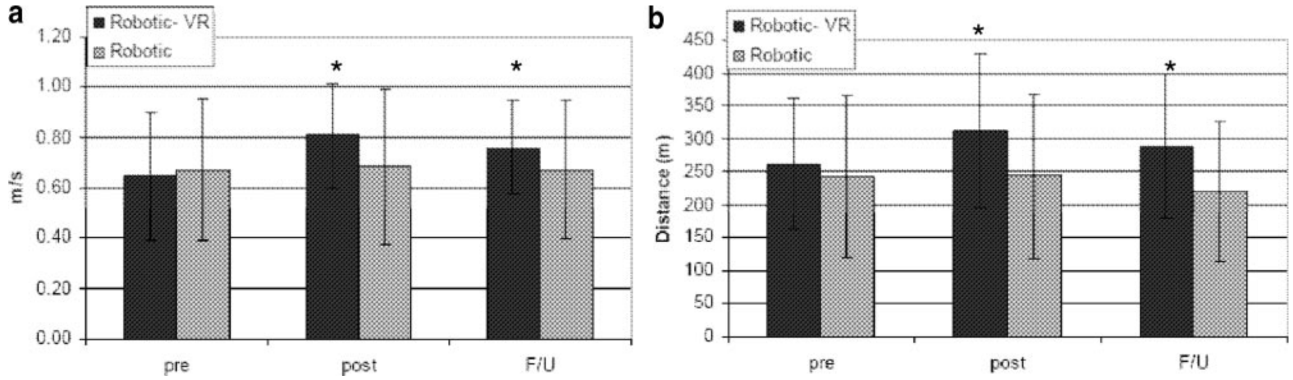

**Figure 2.** Mean and SD for each group before trainin, after training, and at 3-month follow-up. Speed (n=18) (a). The 6-minute walk test (n=17) (b). *Within-group significant differences.

complete a comparable number of repetitions with the robot VR group.

Feedback for the robot VR group was provided by the simulation consisting of knowledge of performance and knowledge of results. The feedback was augmented by the therapist with cues such as direction or timing of the movement. Knowledge of performance for the subjects in the robotic group was provided by the therapist every 30 seconds during each trial and consisted of information regarding the direction, timing, and excursion of the movement. Knowledge of results for the robotic group was provided at the end of the trial and consisted of duration of performance and amount of repetition in the trial. Frequency of therapist cueing was recorded for both groups. The visual analog scale was used to assess fatigue in all subjects. A trial was terminated if the subject reported fatigue >8 of 10 on the visual analog scale or was unable to produce movement for 3 consecutive targets.

## Data Analysis

Clinical gait variables were examined for normality and analyzed using a 2 (groups) by 3 (time) repeated measures ANOVA. The data of 1 subject in the robot VR group was excluded from the distance analysis because it was >2 SD away from the mean.

A secondary analysis was conducted according to initial walking speed. Values within the interquartile range were considered as they represented the majority of subjects, in this case, between ≥0.4 and ≤0.8m/sec, which is considered moderate walking speed. Four subjects in the robot VR group and 3 subjects in the robot alone group had initial walking speeds that were either below or above these values; therefore, these subjects were not considered in this analysis (n=11).

Community-based walking activity as measured by the PAM was analyzed using a 2×2 factorial ANOVA (n=14) and post hoc analysis was performed using a paired *t* test. The number needed to treat[25] was used to analyze the proportion of patients who demonstrated clinically significant improvements in gait speed between the groups. We defined clinically significant improvements in 2 ways: (1) an improvement from 1 functional walking category to another as defined by the functional walking categories of Perry et al[26] (home ambulatory >0.4 m/sec, limited community ambulatory 0.4 to 0.8m/sec, and community ambulatory >0.8 m/sec); and (2) a change in gait speed greater than the smallest real difference of 0.25 m/sec (as defined by Flansbjer et al[27]). For example if a subject's gait speed improved from 0.41 to 0.85 m/sec, this was considered a clinically significant change as the subject improved from being a limited community ambulator to an independent community ambulator. A significance level of 0.05 was set for all analyses.

## Results

All participants completed the training. Subjects in the robot alone group reported fatigue earlier in the sessions compared to subjects in the robot VR group. Those in the robot alone group required more verbal cues and manual cues (28%) to produce movement in the required direction and amplitude. Average total training time for the robot VR group was significantly greater than the robot alone group (492 min vs 451 min; $P$=0.002). The robot alone group also required 11% more rest time than the robot VR group. There were no significant differences between the groups in the number of repetitions performed per session (453.25±88.6 vs 417.68±173.2) or throughout the training (5439±903.73 vs 5012.2±1069.4).

Overground self-selected walking speed was comparable between the groups before training (Table 1). Between-group effects were not statistically significant (F=0.181; df=1; $P$=0.678); however, significant main effects were found across time (F=7.09; df=2; $P$=0.003) with an increase in overground self-selected walking speed of 24% after training, from 0.65 to 0.81m/sec ($P$=0.003) in the robot VR group compared to only 2% (0.67 to 0.68 m/sec; $P$=0.003) in the robot alone group (Figure 2). Improvements in overground self-selected walking speed were sustained at follow-up for the robotic VR group (0.76±0.18 m/sec; $P$=0.013) but not for the robotic group (0.67±0.29 m/sec; $P$=0.974).

Differences between the groups in the distance walked were not significant (F=1.816; df=1; $P$=0.201); however, after training the robotic VR demonstrated an increase of 21% in the 6-minute walk test from 261 m to 312 m ($P$=0.002) but only 0.5% (from 242 to 243.71 m; $P$=0.94) in the robot alone group. Subjects in the robot VR group gained an average of 51 m as compared to1.7 m in the robot alone group (Figure 2).

There was a significant difference between groups in the subgroup analysis (n=11) for both gait speed (F=14.128; df=1; $P$=0.004) and distance walked (F=5.47; df=1; $P$=0.044) after training with gains maintained at 3-month follow-up for subjects in the robotic VR group. Individuals in the robot VR group walked faster and farther than those in the robot alone group.

There were no significant differences between groups before training in any of the community activity measures collected by the PAM. After training, between-group differences were observed for distance walked (F=8.16; df=1; $P$=0.017). Training effects were observed in all parameters. Post hoc analysis reveled that significant changes in perfor-

**Table 2. Spatial Temporal Variables Collected by the PAM**

| | Before Training | | | | |
|---|---|---|---|---|---|
| | Distance, km in 7 Days | N Steps/Day | Average Speed, m/sec | Step Length, m | Top Speed, m/sec |
| Robotic VR | 1.2±0.54 | 1344±43 | 0.53±0.11 | 0.37±0.05 | 0.93±0.27 |
| Robotic | 0.80±0.33 | 1176±39 | 0.61±0.24 | 0.39±0.12 | 0.96±0.3 |

(*Continued*)

Means±SD and percentage of change before and after training.
*P*=significant difference after training within each group.

mance after training were only found in the robotic VR group in distance walked (t=−2.58; $P=0.024$), number of steps per day (t=−2.1; $P=0.045$), average speed (t=−2.58; $P=0.02$), and top speed (t=−2.52; $P=0.023$; Table 2).

Five subjects (55%) in the robot VR group changed walking category[26] after training. Four achieved gait speed >0.8 m/sec after training, placing them in the category of unlimited community ambulation. One subject in the robot VR group increased his gait speed from 0.21 m/sec to 0.43 m/sec, changing his functional ambulation category from household ambulator to limited community ambulator. In contrast, none of the subjects in the robot alone group changed into a different ambulation category. The improvement in gait speed of 2 subjects in the robot VR group exceeded the smallest real difference values of 0.25 m/sec, whereas none of the subjects in the robot alone group accomplished this level of improvement. Number needed to treat for the functional ambulation category was 1.8, and 4.5 for the smallest real difference.

## Discussion

The results reported here support earlier findings that lower extremity training using a robot coupled with VR can improve ambulation for individuals with chronic stroke[17] and extend these findings demonstrating that goal-directed training in a virtual environment was more effective than lower extremity training alone in improving walking of subjects after stroke. Improvements occurred both in laboratory and community based walking measures. These findings suggest that training lower extremity movements in the virtual environment had a greater contribution to improved walking than comparable repetitive movement practice.

Consistent with the neural plasticity literature that supports intensity of the training as well as problem-solving to achieve a behavioral response,[13,14] the robot VR group performed better than the robot alone group. Training for both groups was similar in terms of intensity and number of repetitions performed. The robot alone group trained for 8% less time (on average −3.4 min per session) than the robot VR group but did not demonstrate the same gains in the clinical measures. These subjects reported more fatigue during the training and required more rest periods. These differences could be explained by mental fatigue and the lack of purposeful training associated with the robot alone training. The robot VR group not only received intensive training with multiple repetitions, but those repetitions were also coupled with a task or a goal which required the subjects to control the movement according to targets on the screen.

The changes in gait speed observed in this study are considered clinically meaningful because 5 participants in the robot VR group transitioned into a different ambulation category, whereas none of the subjects in the robotic group achieved this gain. Four of the 5 subjects who increased their walking category were in the moderate gait speed range. This finding is similar to that reported in studies in which BWSTT was used to train gait in a similar group of subjects.[28] Subjects in this study with an initial speed of >0.8 m/sec had a smaller magnitude of change (7% as compared to 17% in the moderate speed level group), suggesting that the lower extremity training in sitting coupled with VR might have had a ceiling effect for subjects with higher walking velocities, who may require a system that would allow them to train in standing.[29]

Improvement in gait speed for 2 of the 9 subjects in the robotic VR group exceeded the smallest real difference, indicating their gait speed change exceeded measurement error and variability. None of the subjects in the robot alone group exhibited a change that exceeded the smallest real difference. Interestingly, the 2 subjects who improved the most were the individuals with the slowest initial walking speed (0.21, 0.41 m/sec). These subjects had an improvement in speed of 0.33 m/sec on average (105%) as compared to 0.16 m/sec (26.6%) for the subjects walking at faster initial walking speeds. This finding taken in combination with the ambulation category findings suggests that the training in sitting may be better-suited for subjects walking at the lower and medium speeds than those at higher speeds. The number needed to treat computation further confirmed that the use of the robotic VR intervention was highly efficacious in improving clinical outcomes.

Improved walking distance was observed mostly in the robotic VR group, which achieved a distance walked of 312±116 m. This distance is contained within the 300 m to 360 m minimal ambulation distance required for independent community mobility.[30,31] It represents an increase of 51 m, which is somewhat less than that reported in the literature for BWSTT.[28] The lower improvement in walking distance relative to BWSTT may be attributed to the dose of training (12 sessions in VR compared to 36 of BWSTT) and to the specificity of training.

An important contribution of this study is the measurement of gait in the community. The subjects in the robotic VR group walked faster and farther after training, with an increase in the number of steps taken per day of 43% (1921±670) as compared to −6.7% for those in the robotic group (1102±424.2), suggesting that robotic VR training had

**Table 2. (Continued)**

| After Training | | | | |
|---|---|---|---|---|
| Distance, km in 7 Days | N Steps/Day | Average Speed, m/sec | Step Length, m | Top Speed, m/sec |
| 2.8±1.74 (141%) $P$=0.024 | 1921±67 (43%) $P$=0.045 | 0.63±0.13 (17.1%) $P$=0.02 | 0.38±0.07 (3.9%) $P$=0.295 | 1.09±0.31 (18.2%) $P$=0.023 |
| 0.73±0.44 (−8.3) $P$=0.250 | 1102±42 (−6.7%) $P$=0.209 | 0.63±0.22 (3.5%) $P$=0.104 | 0.40±0.1 (1.8%) $P$=0.319 | 0.92±0.28 (−4.3%) $P$=0.162 |

greater transfer to functional ambulation in the home and community environment.

Subjects in both groups in this study walked on average 1260±415 steps per day during the pretraining period. This measurement is lower than reported data for individuals after stroke (3035±1944).[32] This discrepancy could be related to the amount of time measured. In this present study, the data collected by the PAM were averaged for measurements taken over 7 days, whereas the reported data from the literature was averaged from recordings of 48 hours. We believe that the longer data collection period might be a more accurate reflection of the true activity performed on a daily basis.

The limited amount of walking activity in both groups as recorded by the PAM compared to age-matched healthy adults in the literature (≈10 000 steps per day),[32] highlights the importance of training to reduce the harmful effects of the vicious cycle of immobility. Increasing community ambulation as a result of training has significant implications for social participation and quality of life for individuals after stroke.

Several features of a VR-based training system may recommend it as a useful tool to augment the existing therapies for gait rehabilitation. These include patient engagement and manipulation of feedback without requiring full-time attention from the clinician, as well as training in multiple environments. For example, both groups had very high adherence (98% for both) and reported high motivation during the training (89/100 and 93/100 for the robotic and robotic VR groups, respectively), suggesting that the role of the clinician is important in motivating the client and VR systems can augment the clinician.[33,34]

Feedback provided by the VR system allowed the clinician to work more efficiently compared to that provided by the robot alone group. Augmented feedback provided knowledge of results of action outcome and knowledge of performance and helped direct subjects' attention to the relevant features of the action to improve the next attempt and is crucial for motor learning and skill acquisition. Although feedback was provided for the robot alone group by the therapist, the task they performed likely lacked salience to produce a carryover effect.[13] A practical consideration was the attention load and time demand exacted from the therapist during the robot alone group was extremely high relative to the VR group.

Although not specifically tested in this study, it may be relevant to compare efficiency and efficacy of VR-based gait interventions with standard of care interventions such as overground walking and body weight-supported treadmill training. Work by Jaffe et al[19] demonstrated greater walking-related benefits after subjects trained clearing virtual steps compared to an overground obstacle course.[19] Most recently, walking on a treadmill was compared to walking on a treadmill linked to a VR system. Individuals with poststroke hemiparesis in the VR treadmill groups improved their gait speed more than those who walked on the treadmill alone.[35] Questions about dosing in VR and what cohort of subjects will benefit from VR compared to other therapies, and what virtual environments are best suited for rehabilitation of walking, will be relevant to answer as well.

It should be noted that in this study there was no significant between-group differences between the 2 groups for gait speed. These differences were likely obscured by subject variability and a small sample size. The inclusion criteria for this study were quite wide, introducing high variability of impairments as well as gait speeds. Although this strengthened the external validity, it might have threatened the internal validity. Differences, however, were revealed in the subgroup analysis.

The uniqueness of this study is that it is the first to our knowledge to compare the effects of lower extremity training by the coupling of a robot with a virtual environment to training with robot and therapist-augmented feedback on walking performance of people after stroke. The study not only evaluated the effects of training in the laboratory setting but also evaluated measures of function in the home and community environment.

## Conclusion

Significant and clinically meaningful improvements in laboratory and real-world measures of walking ability were found after subjects with chronic hemiparesis participated in a 4-week training exercise with an ankle robotic device coupled with VR. As a result of the training, walking speed and distance walked improved and were retained for 3 months. Improvements were also seen in the control group, which trained with only the robotic device without the VR capabilities; however, those were modest and did not transfer to significant functional or behavioral changes. As other virtual environments designed to improve walking for people after stroke are developed and refined, comparisons between these systems will be warranted. In addition, comparison between current methods to improve gait of people after stroke and virtual environment-based applications will be of interest.

## Acknowledgments

The authors thank Dr Grigore Burdea of Rutgers University for permitting the use of the Rutgers Ankle Rehabilitation System; Jeffrey Lewis for assistance refurbishing and installing the system;

Dr Joel Stein for access to the Spaulding Rehabilitation Hospital (SRH) volunteer registry; and Richard Hughes for assistance with data collection.

## Sources of Funding

This work was funded by Motion Analysis Lab at SRH and the Rivers Lab UMDNJ.

## Disclosures

None.

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