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# Effects of virtual reality training on gait biomechanics of individuals post-stroke

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ABSTRACT

*Objective:* To evaluate gait biomechanics after training with a virtual reality (VR) system and to elucidate underlying mechanisms that contributed to the observed functional improvement in gait speed and distance.
*Design:* A single blind randomized control study.
*Setting:* Gait analysis laboratory in a rehabilitation hospital and the community.
*Participants:* Fifteen men and three women with hemiparesis caused by stroke.
*Interventions:* Subjects trained on a six-degree of freedom force-feedback robot interfaced with a VR simulation. Subjects were randomized to either a VR group ($n = 9$) or non-VR group (NVR, $n = 9$). Training was performed three times a week for 4 weeks for approximately 1 h each visit.
*Main outcome measures:* Kinematic and kinetic gait parameters.
*Results:* Subjects in the VR group demonstrated a significantly larger increase in ankle power generation at push-off as a result of training ($p = 0.036$). The VR group had greater change in ankle ROM post-training (19.5%) as compared to the NVR group (3.3%). Significant differences were found in knee ROM on the affected side during stance and swing, with greater change in the VR group. No significant changes were observed in kinematics or kinetics of the hip post-training.
*Conclusions:* These findings are encouraging because they support the potential for recovery of force and power of the lower extremity for individuals with chronic hemiparesis. It is likely that the effects of training included improved motor control at the ankle, which enabled the cascade of changes that produced the functional improvements seen after training.

## 1. Introduction

The gait pattern of individuals post-stroke is often characterized by delays in movement initiation, inefficient movement patterns on the hemiparetic side, decreased stance time on the paretic side, and premature toe off during terminal stance, as compared to healthy adults [1,2]. Closer analyses of the gait mechanics of individuals post-stroke reveals decreased excursion and lower than normal magnitudes of power generation at all joints of both the affected and unaffected lower extremities [2–4]. Typical gait changes include reduced or loss of knee flexion in stance, loss of dorsiflexion of the ankle at initial contact and during swing, and lack of ankle plantar flexion (push-off) at terminal stance [5].

A growing body of evidence suggests that intensive, goal directed therapy improves function for individuals in both the acute and chronic stages post-stroke [6,7]. Intensive task-specific exercise increases ankle push-off and hip pull-off power generation and walking speed [8–10]. Although current therapeutic interventions for individuals post-stroke emphasize intensive practice of functional tasks rather than training isolated movement patterns [11], one could argue that training need not be task-specific, if training addresses the relevant kinematic or kinetic features of the movement. Specifically for gait, one might engage individuals in training that emphasizes ankle push-off, even if the training is not walking.

Previously we reported that lower extremity training with a robotic-VR integrated system produced gains in over-ground walking [12–14]. Training in these studies involved a navigation task, in which individuals' post-stroke used their ankle as an interface to a virtual environment. Task-specific elements included ankle coordination with an emphasis on reciprocal intra-segmental movement and ankle kinetics in a closed chain position [15]. We speculated that the functional improvements in gait were the

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product of increased force and power generation at the ankle as a result of the combination of task-training and specificity of training the distal effector [14]. We hypothesized that temporal and spatial features of ankle kinetics would be altered in the group that trained with virtual reality coupled with the robot, but not the group that trained with the robot alone. Moreover, that ankle push-off power on the stroke affected side would increase in the robot-VR group. The purpose of this paper is to report results from the analysis of gait biomechanics and elucidate underlying mechanisms that contributed to the observed gait speed changes.

## 2. Methods

### 2.1. Participants

Fifteen men and three women with hemiparesis caused by stroke were enrolled in this study. They were all in the chronic phase post-stroke and exhibited residual gait deficits. All subjects had partial anti-gravity dorsiflexion and were able to walk at least 50 ft. without the assistance of a person and were not receiving concurrent therapy. All subjects had sufficient communicative and cognitive abilities to participate. There were no differences between the groups in gender (83% men), side of stroke (left/right; 10/8), mean age (62 years, 41–75 range) or chronicity post-stroke (greater than 2 years). Both groups had a moderate lower extremity impairment (mean Fugl Meyer score 23; range 15–28), slight risk for falls (mean Berg Balance score 47; 31–55 range) and comparable initial walking speed pre-intervention (mean 0.6 m/s; 0.13–1.1 m/s). All procedures were approved by the IRB's of Spaulding rehabilitation hospital and UMDNJ, and all subjects gave informed consent.

### 2.2. Design

A single blinded randomized control study design was employed. Subjects were evaluated 1 week before and after participating in a 4-week training program. Follow-up evaluations occurred at 3 months post-training.

The majority of the subjects walked with an ankle foot orthosis (AFO) device (12/18), therefore, gait trials were collected under two conditions; barefoot and while wearing shoes and orthotics. The data derived from the gait analyses included bilateral spatiotemporal parameters, and kinematics and kinetics of the ankle, knee and hip joints during the stance and swing phases of gait.

Data were captured using an eight-camera motion capture system (Vicon 512, Vicon Peak, Oxford, UK) incorporating two embedded force platforms (AMTI force platforms, Watertown, MA, USA) in a 7 m walkway. Sixteen passive reflective markers were placed over anatomical landmarks of the pelvis, legs, and feet according to the standard Vicon Plug-in Gait model. All subjects walked unassisted except for 2 subjects who walked with a straight cane. Five successful walking trials defined as a single foot contact of each leg on the force platforms were collected in each condition. Marker trajectories and ground reaction forces were sampled at 120 Hz for the calculation of lower extremity joint kinetics and normalized to body mass and height.

### 2.3. Intervention

Subjects trained on the Rutgers ankle rehabilitation system (RARS), a six-degree of freedom Stewart platform force-feedback system. The system allows individuals to exercise the lower extremity by navigating through a virtual environment (VE) displayed on a desktop computer. The development and testing of the device has been reported elsewhere [13,16,17].

Subjects were randomized to either a VR group ($n = 9$) or NVR group ($n = 9$). Training was performed three times a week for 4 weeks for approximately 1 h each visit. Subjects in both groups were seated on a raised chair approximately 1 m in front of a computer with the screen at eye level. The affected foot, without the orthotic device, was placed on the platform and strapped comfortably, with the ankle in a neutral position and the knee and hip at 90 degree angles. Subjects were asked to perform movements using only the ankle in the direction of dorsiflexion, plantarflexion, inversion, eversion, and a combination of these movements. Baseline force, speed and excursion performances were measured using the robotic system at the beginning of each session and were used as a reference for the exercise protocol. Training intensity and progression of the protocol was based on previous studies [12,13] and were adjusted for individual subjects relative to accuracy and reported fatigue, using the visual analog scale (VAS) [14].

Subjects in the VR group executed the exercises by using foot movements to navigate a plane or boat through a VE that contained a series of targets. The position and timing of the targets were manipulated to ensure training included discrete and combined ankle movements. Subjects in the NVR group received similar exercises as the VR group but without the feedback provided by the VE; the computer screen was occluded to block visual and auditory feedback. A therapist instructed the subjects as to the direction of movement and a metronome was used to pace for timing, to ensure a comparable for number of repetitions of each ankle joint movement between the groups.

### 2.4. Data analysis

Means and standard deviations were calculated for all dependent variables. Histograms and frequency distributions were constructed to evaluate the normality and homogenic distribution of the dependent variables. Spatiotemporal gait parameters, including self-selected walking speed and joint kinetics and kinematics, were calculated as the mean of 5 walking trials. Kinetic data included ankle moments, during stance and pre-swing, knee flexor moment, produced at the knee during stance and at push-off, hip flexor moment at initial swing and power at the ankle, knee and hip. Kinematic parameters included range of motion (ROM) of the ankle and hip joints during the gait cycle, and ROM of the knee joint during stance and swing phases separately. Onset of push-off was defined as the instance (% of gait cycle) of gradient decline of the ankle moment curve after peaking at mid-stance.

All data were evaluated using a two factorial (training regime × time) repeated measures analysis of variance to assess the immediate effects of training as well as any retention effects (follow-up). Data for barefoot and shoe conditions were each analyzed separately. With the exception of the kinematics data, all subjects were assessed in all analyses. In the barefoot condition, one subject in the VR group and one subject in the NVR group were identified as outliers (with values 2 standard deviations above the mean); therefore their data were excluded from the analysis. Significance level for all analyses was set at $\alpha = 0.05$.

## 3. Results

All participants completed the 12 training sessions with no adverse events. There was no significant difference between the groups for number of ankle movement repetitions ($t = 0.91$, $p = 0.18$).

### 3.1. Self-selected walking speed

Self-selected walking speed (SSWS) for the VR group improved significantly ($F = 7.09$, $p = 0.003$) by 24%, from 0.65 to 0.81 m/s compared to only 2% (0.67–0.68 m/s, $p = 0.8$) in the NVR group.

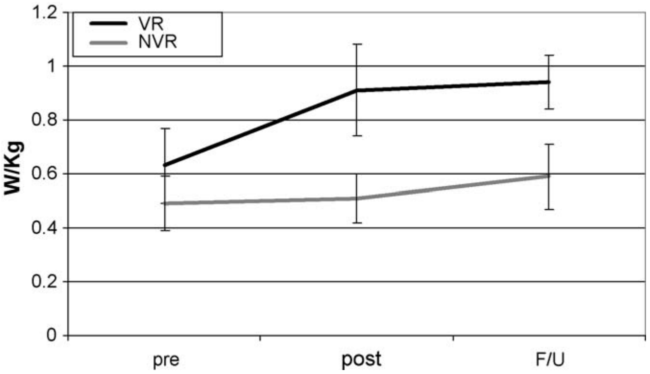

**Fig. 1.** Mean and standard error of ankle power at push-off (in the barefoot condition) pre-training, post-training and at follow-up (F/U) for both groups ($n = 9$/group pre and post, $n = 7$/group at F/U).

Improvements in SSWS were sustained at follow-up for the VR group ($0.76 \pm 0.18$ m/s, $p = 0.013$) and were unchanged for the NVR group ($0.67 \pm 0.29$ m/s, $p = 0.97$) [12].

### 3.2. Gait kinetics

Ankle kinetics were significantly different between groups in the barefoot condition. The subjects in the VR group had a higher percentage of change in ankle moment at push-off, from $0.74 \pm 0.24$ Nm/kg to $0.90 \pm 0.31$ Nm/kg (21%) as compared to the NVR group; from $0.68 \pm 0.17$ Nm/kg to $0.67 \pm 0.08$ Nm/kg (−1.5%). Differences between groups were found in ankle power at push-off ($F = 6.302$, $p = 0.036$), with subjects in the VR group demonstrating a large increase in ankle power as a result of training from $0.63 \pm 0.28$ W/kg to $0.91 \pm 0.45$ W/kg (44%) as compared to only 4% change ($0.5 \pm 0.27$ W/kg to $0.52 \pm 0.26$ W/kg) in the NVR group. Gains in ankle power were maintained for the VR group at follow-up (0.94 W/kg) (Fig. 1). No differences between groups after training were found in ankle kinetics for the shoe condition.

### 3.3. Gait kinematics

In the barefoot condition, ankle ROM increased significantly for both groups (19.5% and 3.3% for the VR and NVR groups, respectively). Participants in the VR group had significantly greater increases in knee ROM on the affected side during stance (34%) and swing (15.7%); compared to the NVR group (7.2% and 3.9%).

Ankle ($20.65 \pm 5.8$) and knee range during stance ($15.61 \pm 5.92$) were sustained at follow-up but only for the VR group ($p = 0.07$) (Table 1).

During ambulation with shoes, there were no significant differences between groups in kinematics (Fig. 2). As expected, because participants wore their orthotics with their shoes, neither group had differences in ankle ROM; however, both groups demonstrated kinematic changes in the knee joint after training. Subjects in the VR group significantly increased knee range during stance from 14.9 to 20.4 degrees (36%) whereas the NVR group significantly decreased knee range of motion during stance but also increased significantly swing range, from 28.1 to 37.0 degrees (31%). Both groups maintained improvements in knee ROM at follow-up, as compared to pre-training (knee ROM during stance for the VR $17.2 \pm 8.1$ and knee ROM during swing for the NVR group $32.3 \pm 9.7$).

### 3.4. Onset of push-off

A significant change in push-off onset was observed ($F = 9.372$, $p = 0.003$) with significant differences between the groups after

**Table 1**
Mean ± standard deviations of the joint angle ROM (degrees) in barefoot condition pre- and post-training for both groups.

| Joint angles (degrees)[a] | VR group | | | | NVR group (no VR) | | | |
|---|---|---|---|---|---|---|---|---|
| | Barefoot pre | | Barefoot post | | Barefoot pre | | Barefoot post | |
| | Affected | Non-affected | Affected | Non-affected | Affected | Non-affected | Affected | Non-affected |
| Hip range | $29.3 \pm 7.4$ | $40.4 \pm 6.3$ | $32.7 \pm 11.3$ (11.2)$^{NS}$ | $40 \pm 5.4$ (−0.9)$^{NS}$ | $32.6 \pm 13.4$ | $36.7 \pm 3.2$ | $32.3 \pm 13.6$ (−0.9)$^{NS}$ | $36.7 \pm 5.1$ (−0.1)$^{NS}$ |
| Knee stance range | $12.5 \pm 4.7$ | $13.4 \pm 2.2$ | $17.3 \pm 3.4$ (38.8)$^{*}$ | $19.2 \pm 6.7$ (43.3)$^{NS}$ | $12.5 \pm 4.9$ | $14.2 \pm 3.7$ | $13.4 \pm 4.5$ (7)$^{NS}$ | $15.8 \pm 3.1$ (6.2)$^{NS}$ |
| Knee swing range | $32.9 \pm 7.2$ | $45.8 \pm 3.8$ | $38.1 \pm 10.7$ (15.7)$^{*}$ | $52.2 \pm 4.3$ (13.8)$^{*}$ | $31.3 \pm 13.8$ | $58.6 \pm 2.4$ | $32.5 \pm 17.0$ (3.9)$^{NS}$ | $58.5 \pm 6.2$ (−0.03)$^{NS}$ |
| Ankle range | $17.4 \pm 2.6$ | $23.8 \pm 6.7$ | $20.9 \pm 8.1$ (19.5)$^{*}$ | $31.5 \pm 2.1$ (32.6)$^{NS}$ | $17.7 \pm 6.3$ | $20.6 \pm 6.7$ | $18.3 \pm 7.1$ (3.3)$^{*}$ | $19.2 \pm 2.4$ (−6.8)$^{NS}$ |

() = percent of difference between pre- and post-training ($N = 16$).
[a] Joint angle range = maximum range – minimum range.
[*] Significant at 0.05.
[NS] Not significant.

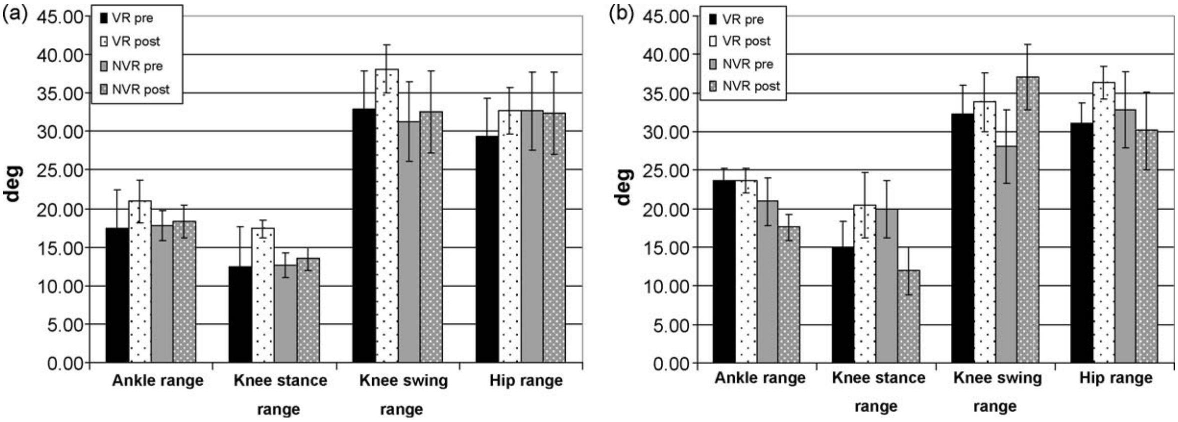

**Fig. 2.** Mean kinematic angular range of excursion and standard errors, pre- and post-training for both groups during: (a) barefoot walking ($n = 16$) and (b) walking with shoes ($n = 18$).

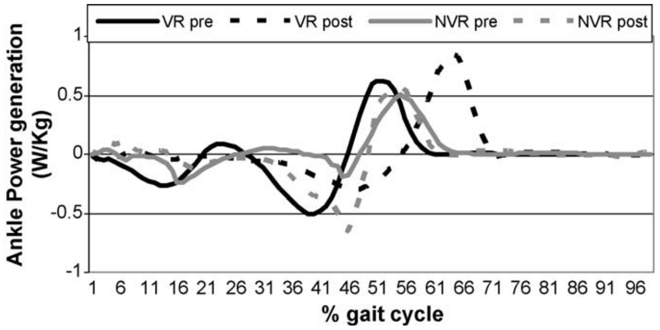

**Fig. 3.** Time series figure. The magnitude and timing of ankle push-off as reflected in percentage of the gait cycle. The represented lines are the average performance of five trials of the paretic limb in each group pre- and post-training.

training ($p = 0.023$). Prior to training, the majority of subjects in both groups ($n = 13$) initiated push-off prematurely compared to normative data [4]. On average, the onset of ankle push-off for both groups was at 55.0% of the gait cycle. After training the VR group initiated push-off at 57.7% of the gait cycle, while the NVR group demonstrated no change (Fig. 3).

## 4. Discussion

The purpose of this paper was to report on the gait biomechanics and elucidate underlying mechanisms that contributed to the gait speed changes observed after VR training. The results reported here support earlier findings that task-based VR training can improve gait function for individuals with chronic stroke [12,13,18] and that coupling task based and specificity of training using VR training of the lower extremity is more effective than robotic training alone. More specifically we hypothesized that task-based VR ankle training in a closed kinetic chain would transfer to increase plantar flexion power at push in gait.

Pre-training, kinetic profiles were impaired in the ankle for all subjects with a decrease of as much as 50% from the normative power values generated during push-off. The ankle profiles of the affected side showed an increase in the peak plantar flexion moment, and ankle power generation, for both groups but were significantly greater for the VR group. These results confirm and extend previous findings in studies using the RARS device [12,13] which reported that after training, subjects had improved lower extremity strength measured with dynamometry of the paretic limb. The novelty of the findings reported here is that force generation associated gains were evaluated during gait.

Task-training combined with task specificity is highlighted when comparing our findings with others. Teixeira-Salmela et al. [19] used a task-specific training protocol combining treadmill training with training specificity using muscle strengthening and physical conditioning. They reported a near-doubling of the peak ankle power burst on the affected side following 10 weeks of training. The power increase was related to a mean increase in gait speed of 0.16 m/s. In our study, the percentage of change for both magnitude of power and mean walking speed were similar to that reported by Teixera-Salmela et al, although subjects had a lower average initial ankle push-off power burst. Our results are of interest because we trained in the seated position over 4 weeks, while Texeira-Salmela et al. trained in standing over 10 weeks with walking. The training in our study was not task (gait) specific; however, the navigation task contained relevant features of walking and addressed the impairment of force generation (measured with gait kinetics at push-off).

The control group in our study had similar findings to others that have used impairment level training. Kim et al. found little change in the capacity to produce ankle torque, and no transfer into faster walking speed after 6 weeks of voluntary or passive isokinetic knee exercises in individuals with chronic stroke [20]. The isokinetic training was provided 3 times a week for 6 weeks, but much like the NVR training provided no visual and auditory feedback. The absence of task-specific training could be the factor limiting carry over into functional tasks.

The major changes in joint kinematics during barefoot walking observed post-training were represented by overall increases in ankle and knee ROM during stance and swing. Training effects in the ankle joint were expected for both groups since the foot–ankle complex was used to control the robotic device. There might have been some stabilization effects in the knee and hip during training but as the training was performed in sitting, the kinematic changes that were observed in the knee and hip are likely related to intralimb changes secondary to improved control of the ankle.

Normal foot–ankle mechanics during terminal stance and pre-swing are necessary to allow knee flexion to begin pre-swing movement [21]. Furthermore, during stance phase, insufficient activity of the ankle plantar flexors can result in poor control of the tibia [22]. The most frequently adopted compensation pattern is the knee position during mid-stance, with the knee either hyper-extending to rely on passive knee stability, or collapsing into flexion. With increased strength, however, improved tibial control can result in less residual flexion, better extension [22]. Distal control achieved through training could lead to improved proximal control [22]. In this study, significant changes in knee ROM during stance were found after training only for the subjects in the VR group. The changes in knee range during stance are likely to be associated with an increase in ankle control and strength that allowed for better tibial progression. The increase in flexion at the knee might be a compensatory mechanism and not a controlled pattern, but knee flexion profiles post-training demonstrated ROMs that were closer to normative values in both shape and magnitude, suggesting a controlled movement. Interestingly, knee stance improvements were only significant in the VR group. This finding suggests that motor control capabilities that were produced during training were specific to the training with the VR simulation, and this control was transferable to weight bearing activities.

During swing, there was an increase in knee ROM for both groups but it was moderate for the VR group (4%) as compared to the NVR group (32%). After training, subjects in the NVR group had a marked increase in knee ROM on the non-affected side. Increased excursion of the unaffected knee may be related to either increases in speed or a compensatory strategy [1]. For the NVR group, there was no increase in velocity post-training, making it likely that this increase in swing ROM of the unaffected knee is a compensation required to advance the limb forward while increasing step length and providing clearance of the foot.

Individuals with gait speed less than 0.40 m/s had especially low values of moments and powers, which were almost zero during push-off pre-training. Richards et al. [8] found that about 27% of the increase in walking speed for individuals post-stroke is associated with augmented power of the plantarflexors at push-off on the affected side. Jonkers et al. [18] found that impaired ankle power generation combined with saturation of hip power generation limits the potential to increase walking speed in lower functioning hemiparetic subjects [23]. Our findings concur with these studies as the individuals with the largest gains in ankle power were also those with the greatest gains in gait speed. This further re-enforces the relevance of specificity of training the distal effector.

The findings of this study are encouraging because they support the potential for recovery of force and power of the lower extremity for individuals with chronic hemiparesis. While this paper focused on the immediate effects of the training to provide a mechanistic explanation for the changes in gait speed, it is interesting to note that most of the kinetic and kinematic changes were sustained at follow-up. The findings also suggest that it may be possible to train at the task-level using specificity of training; which may be a relevant intervention strategy when task-specific training is not feasible. We speculate that the effects of training were improved motor control at the ankle, which enabled the cascade of changes that produced the functional improvements seen after training. Likely there are intra-segmental changes in ankle coordination that require further scrutiny.

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