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Abstract

Improvements in task performance due to repeated testing have previously been documented in healthy and patient populations. The existence of a similar change in performance due to repeated testing has not been previously investigated at the level of gait kinematics in the post-stroke population. The presence of such changes may define the number of testing sessions necessary for measuring a stable baseline of pre-training gait performance, which is a necessary prerequisite for determining the effectiveness of gait interventions. Considering the emergence of treadmills as a popular tool for gait evaluation and retraining and the common addition of functional electrical stimulation (FES) to gait retraining protocols, the stability of gait kinematics during the repeated testing of post-stroke individuals on a treadmill, either with or without FES, needs to be determined. Nine individuals (age: 58.1 +/− 7.3 years), with hemi-paresis secondary to a stroke (onset: 7.3 +/− 6.0 years) participated in this study. An 8-camera motion analysis system was used to measure sagittal plane knee and ankle joint kinematics. Gait kinematics were compared across two (N=9) and five (N=5) testing sessions. No consistent changes in knee or ankle kinematics were observed during repeated testing. These findings indicate that clinicians and researchers may not need to spend valuable time and resources performing multiple testing and acclimatization sessions when assessing baseline gait kinematics in the post-stroke population for use in determining the effectiveness of gait interventions.

Keywords

Treadmill; Repeated Testing; Functional Electrical Stimulation (FES); Kinematics; Stroke

INTRODUCTION

Over 7.7 million Americans are currently living with post-stroke disabilities. Many of these disabilities are life-altering and necessitate physical rehabilitation. Walking dysfunction is one such disability, and has been linked to delayed hospital discharge to home [1], delayed

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return to work [2], and limited community participation [1]. For the vast majority of stroke survivors, improved walking ability is thus the ultimate goal of rehabilitation [3]. Accordingly, considerable time, effort, and resources are spent on gait retraining during conventional post-stroke rehabilitation. However, residual gait deficits often still remain, and compensations such as “stiff-legged” [4] and circumduction gait [5, 6] eventually result. These gait deficits often increase energy expenditure, diminish endurance, and increase the likelihood of falls [6–9].

Novel gait retraining interventions have recently been introduced to address these residual gait deficits [7, 10–13]. In this study, we explore two such interventions: treadmill walking and functional electrical stimulation (FES), which is a popular targeted intervention for the treatment of foot drop [14–17]. Appropriate use of these interventions is contingent upon evidence for their effectiveness. An evaluation of an intervention’s effectiveness necessitates at least two testing sessions, typically in the form of pre- and post- intervention testing. Evidence for an intervention’s effectiveness requires not only the use of valid and reliable outcome measures, but also on knowledge of the effect that repeated testing may have on performance. Indeed, if mere repeated testing yields *systematic* changes in performance across testing sessions, then the likelihood that post-intervention performance changes are not therapy-related, but are merely artifacts of repeated testing, is increased. Consequently, additional testing sessions may be necessary before stabilization of baseline performance can occur and post-intervention performance changes can be considered an accurate reflection of an intervention’s effect.

While few studies in both healthy and patient populations have provided direct evidence for either the existence or absence of an effect of repeated testing on performance, it is often anticipated and controlled for [18–20]. Researchers have used the better [18], the average [19], or the second [20] of two collected measures when conducting baseline measurements of variables such as maximal force [18–20], gait velocity and stair-climbing power [19] to minimize improvements due to repeated testing. These methods are common, and while it is clear that an accurate reflection of baseline performance is their purpose, the criterion by which they are selected is not identified [18–20]. In both able-bodied individuals and various patient populations, improvements in task performance have been observed with the repeated testing of the six-minute walk test (6MWT) [20–24]. These improvements in performance across testing sessions have ranged from 5% to 33%, with incremental increases occurring across three sessions in healthy adults [20], and across two sessions in patients with fibromyalgia [23] and chronic cardiac and pulmonary disease [24]. The underlying mechanisms of this phenomenon are unknown, but researchers have postulated that these improvements may result from improved coordination, finding optimal stride length, or even overcoming anxiety [25]. Because the 6MWT is correlated with walking ability and function in the post stroke population [26], these previous findings may have significant implications on the number of testing sessions that may be necessary to achieve a stable baseline of post-stroke gait performance.

It is currently unknown whether repeated gait testing on a treadmill, either with or without the addition of FES, has any effect on the gait kinematics of the post-stroke population. With the increased prevalence of treadmills as tools for gait evaluation and retraining, it is important to determine the effects of repeated treadmill testing on gait performance. Also, considering the common addition of FES to post-stroke gait retraining protocols [14–17], understanding the effects of electrical stimulation on the consistency of post-stroke gait is also warranted. Thus, the purpose of this study was to determine if the mere repeated testing of post-stroke gait during treadmill walking, with and without the addition of FES for dorsiflexor assist, produced immediate changes in knee and ankle kinematics.

METHODS

Nine subjects with hemiparesis secondary to a stroke participated in this study (Table 1). Inclusion criteria included at least six months following a stroke involving the cerebral cortical regions, the ability to walk for five minutes at a self-selected walking speed, and sufficient passive ankle ROM to allow the ankle to be dorsiflexed to within 5 degrees of a neutral position (i.e. 5 degrees of plantarflexion). Exclusion criteria included substantial cognitive deficits, severe aphasia, cerebellar involvement, and any preexisting conditions affecting walking function. All nine subjects participated in two testing sessions (2-session group). Due to scheduling conflicts, only five of these nine subjects were able to participate in an additional three testing sessions (5-session group). Subjects were asked to walk on a treadmill with and without FES delivered to the ankle dorsiflexor musculature during the swing phase of gait. All subjects signed informed-consent forms previously approved by the human subjects review board of the University of Delaware.

In this paper, we report data collected under 2 different walking conditions: (1) treadmill walking without FES (noFES), and (2) treadmill walking with dorsiflexor muscle FES (FES). A single testing session consisted of 18 treadmill walking trials of 20 to 40 seconds each. Rest intervals of 5 to 10 minutes were provided between consecutive trials. The noFES data collection always occurred at the beginning (1st trial) of each testing session. The FES data collection occurred during a subsequent walking trial, but the trial number was randomized. Gait speed during each walking trial was set at the participant's self-selected over ground walking speed. Data collection commenced a few seconds after the target treadmill speed was reached; thus subjects were provided with an opportunity to practice taking several steps on the treadmill before data were collected. For safety, subjects held onto a handrail located on the front end of the treadmill while walking. All subjects wore a harness that was connected to overhead support; no body weight was supported by the harness.

The data presented in this paper are part of a larger study previously completed in our laboratory; greater detail of our experimental methodology can be found in a previous paper [27]. Surface electrical stimulation electrodes (2”×2”; TENS Products, Grand Lake, Colo) and a Grass S8800 stimulator in combination with a Grass model SIU8TB stimulus isolation unit was used to deliver the electrical stimulation (Grass Instrument Co, Quincy, Mass). An 8-camera motion analysis system (Vicon 5.2, Oxford, England) was used to collect marker data at 100 Hz during walking, with and without dorsiflexor FES, on a split-belt treadmill instrumented with two 6° of freedom force platforms (AMTI, Watertown, Mass).

Data Processing

Marker trajectories and ground-reaction force data were low pass filtered (Butterworth fourth order, phase lag) at 6 and 30 Hz, respectively, with the use of commercial software (Visual 3D; C-Motion, Rockville, MD). Vertical ground-reaction forces were used to determine gait events.

Dependent Variables

Because an increase in swing phase ankle angle is the primary kinematic goal of the FES provided in this study, and because we have previously shown that changes in swing phase knee angle occur with FES [27], peak swing phase ankle dorsiflexion and knee flexion angles were our variables of interest. For each subject, an equal number of consecutive strides (at least 9) were used across sessions to compute an average peak knee flexion and peak ankle dorsiflexion angle for each session. Peak knee flexion and ankle dorsiflexion angle stride-to-stride standard deviation were also computed for each session, and stride-to-stride variance was subsequently calculated as the square root of this stride-to-stride standard deviation.

Statistical Analysis

An a priori power analysis using the G Power 3 software showed that with nine subjects, at α =.05 we would have 92% power to detect a .5 (medium) effect size. Thus, statistical analysis was performed using SPSS for the 2-session group (N=9), and consisted of two-way repeated measures ANOVAs to assess main effects of stimulation, session, and an interaction between stimulation and session for peak knee angle, ankle angle, and stride-to-stride variance. For the 5-session group (N=5), because of the small sample size, only descriptive statistics were assessed. In addition, peak knee angle, ankle angle, and stride-to-stride variance changes across sessions (across-session) were compared to known minimal detectable change (MDC) values [28] to determine significance.

RESULTS

Complete data sets were collected for 8 of 9 subjects (Figures 1 and 2). Due to problems with data collection during testing session one for subject 36, data for the noFES condition from another trial within the testing session were substituted for data for the noFES condition from the beginning of the testing session.

2-Session Data (N=9)

Analysis of *peak ankle angle* data revealed a main effect of stimulation (FES increased ankle angle) (p=.03), no main effect of session (p=.89), and no interaction effect (p=.72) **(see** Figure 1). Similarly, for *peak knee angle*, a main effect of stimulation was observed (FES decreased knee angle) (p=.04), but neither a main effect of session (p=.64) nor an interaction effect (p=.43) were found. For *peak ankle angle stride-to-stride variance,* a main effect of stimulation was observed (FES decreased variance) (p=.005) and an overall effect of session was observed (greater ankle angle variance during the 2nd session) (p=.04). No interaction effect (p=.07) was found. Similarly, for *peak knee angle stride-to-stride variance,* a main effect of stimulation was observed (FES decreased peak knee angle stride-to-stride variance) (p=.05), but neither a main effect of session (p=.73) nor an interaction effect (p=.46) were found .

5-Session Data (N=5)

MDC values have been reported for peak ankle (4.9º) and peak knee angle (5.7º) but not for peak ankle and peak knee stride-to-stride variances [28]. For both the FES and noFES conditions, the average across-session kinematic changes for *peak ankle angle* and *peak knee angle* were not greater than the known MDCs **(see** Figure 2) . No consistent changes were present for *peak ankle* and *knee angle stride-to-stride variance*. Inspection of individual subject data revealed no systematic across-session changes.

DISCUSSION

The determination of an intervention's effectiveness is typically made after comparison of pre- and post-intervention performance measures. However, the mere repeated testing of gait could produce either improvements or declines in gait performance. These performance changes could lead to false conclusions of either effectiveness or ineffectiveness. Thus, an accurate appraisal of effectiveness requires a stable pre-intervention measurement of baseline gait performance, which may necessitate multiple testing sessions. Hence, the purpose of this study was to determine if the repeated exposure to two novel gait retraining interventions – 1) treadmill walking and 2) treadmill walking combined with dorsiflexor

FES – produced *systematic* changes in post-stroke gait kinematics, and if these changes were stabilized with additional testing sessions. Our results show that whether measured across two or five testing sessions, no *systematic* changes in peak knee and ankle angle means and variances were observed except for an overall increase in ankle angle variance across two sessions. However, this finding did not persist across five testing sessions as no consistent patterns of change emerged across subjects. Our study, therefore, demonstrates that post-stroke knee and ankle gait kinematics do not exhibit systematic changes across multiple treadmill walking sessions. This stability of post-stroke knee and ankle gait kinematics is further supported by our similar finding of no systematic changes in gait kinematics across testing sessions even with the addition of FES during walking.

This finding of no systematic changes in kinematic performance across multiple testing sessions for post-stroke individuals is in contrast to the learning effects produced during the repeated testing of the 6-minute walk test (6MWT) in young healthy adults [20], individuals with down syndrome [21], patients with fibromyalgia [23], and those with chronic cardiac and pulmonary disease [24]. Furthermore, our finding calls into question whether the many precautionary actions taken by researchers in anticipation of an interaction between testing and performance, such as those described earlier in this paper [18–20], are indeed necessary without direct evidence for such an interaction.

The lack of systematic changes in gait performance due to repeated testing that were observed during this study may be explained by the lack of knowledge of results provided to the subjects during testing. Force production testing, velocity testing, and 6MWT studies all inherently provide some knowledge of results as subjects are generally aware of their performance even without external feedback, and thus some learning is expected. However, individuals are typically not aware of their gait kinematics during walking; thus, without external feedback, no knowledge of results is provided during testing and any possibility of learning is minimized. Exploration of an interaction between post-stroke gait testing and performance when knowledge of results is provided may be an interesting direction for future study.

The lack of systematic changes in performance due to repeated testing that were observed in this study may also be due to the nature of gait testing. An individual's initial performance on any given outcome measure may be negatively impacted by factors such as lack of familiarity with the testing procedures and anxiety. These factors can be overcome with practice that can be provided via several testing or acclimatization sessions. Improvements in performance that may emerge during these subsequent sessions likely do not represent motor learning; rather, these improvements may reflect the emergence of true baseline abilities that were hindered by the lack of familiarity with the procedures or anxiety. However, as was described in the methods section of this paper, for the present study subjects had the opportunity to familiarize themselves with the procedures by taking several practice steps immediately before data began to be recorded. This may explain why multiple testing sessions may not be necessary for gait testing on a treadmill, while still necessary for measures such as force production and 6MWT performance. This is fortunate as the considerable time and resources necessary to conduct multiple sessions of motion analysis are significantly higher than those needed to repeat the 6MWT or re-measure maximal force production. Thus, our findings may be of substantial clinical and research value as they suggest that there is little advantage to collecting more than one testing session when determining post-stroke treadmill walking ability, with or without the addition of FES.

The absence of systematic changes in performance due to repeated treadmill testing in the present study may also be related to a decreased motor learning ability in post-stroke and possibly other neurologically impaired patient populations. In the young, healthy population, improvements in 6MWT performance due to repeated testing were maintained for as long as two months, and additional improvements were observed after another round of repeated testing [20]. This finding in a healthy population, as compared to a neurologically impaired population, suggests that some populations may have higher motor-learning thresholds as compared to their neurologically unimpaired counterparts. Indeed, a restricted learning capacity was postulated as a reason for the absence of a learning effect in some adults with Down syndrome [21].

Another possible reason for our observation of no changes in gait performance during repeated treadmill testing is our small sample size; however, the results of our power analysis indicate that this study was adequately powered. Furthermore, because we were able to detect the modest differences that were present between the FES and noFES conditions (**see** Figures 1 and 2), we are confident that our equipment and evaluation methodology were both highly sensitive and reliable, and that we would have been able to detect changes in performance due to repeated testing if they had existed. Thus, while future studies with a larger sample size may increase the generalizability of our results, we do not believe they will contradict our findings.

It should be noted that while this study has demonstrated that no *systematic* changes occur in post-stroke gait kinematics across testing sessions, *random* variations do exist for individual subjects **(see** Figure 2). This random variability – which has been ascribed to test-retest errors, and the increased inherent day-to-day variability in post-stroke walking patterns as compared to neurologically unimpaired individuals [28–30] – can effectively be accounted for through the use of MDC scores [28]. Specifics regarding the appropriate use of MDC scores can be found in a previous paper from our lab [28]; however, if repeated testing did produce changes in gait performance, relying solely on MDC scores to determine "real change" would be insufficient as changes in performance due to repeated testing may be greater than the MDC, thus yielding a false impression of an intervention's effectiveness. Our finding of no interaction between post-stroke gait testing and performance therefore affords clinicians and researchers the confident use of MDC scores when determining the effectiveness of post-stroke treadmill walking, with and without the addition of FES.

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- Post-stroke knee and ankle kinematics show no consistent change during repeated treadmill testing.
- This finding persists even with the addition of ankle dorsiflexor functional electrical stimulation.
- These results suggest that only one testing session may be necessary when assessing post-stroke gait kinematics.

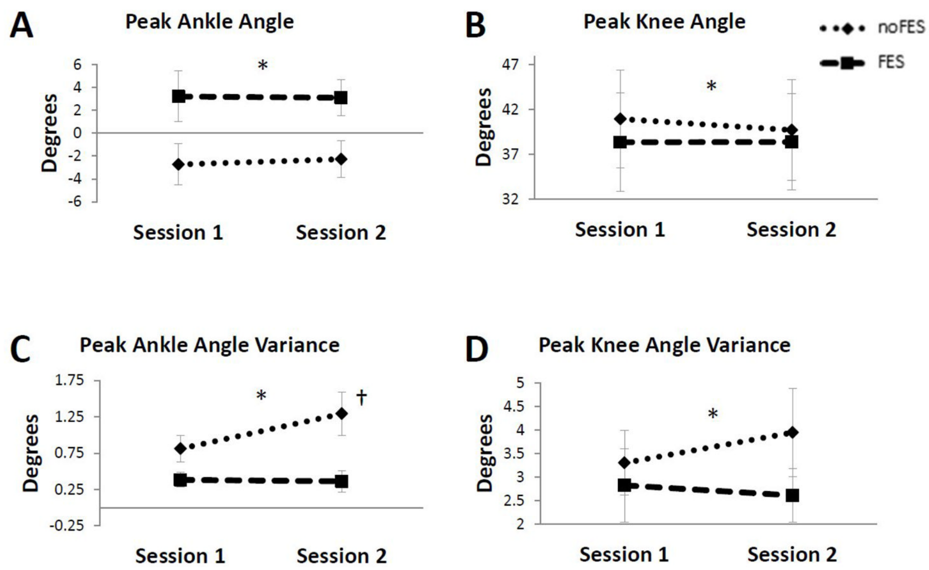

Figure 1.
presents the mean values for peak ankle and knee angles (panels A and B) and variances (panels C and D) for the 2-session group (N=9). Each panel (A–D) presents across-session changes for both the FES and noFES conditions.

* denotes a main effect of stimulation between conditions ($p \leq .05$).

† denotes a main effect of session for a condition ($p \leq .05$).

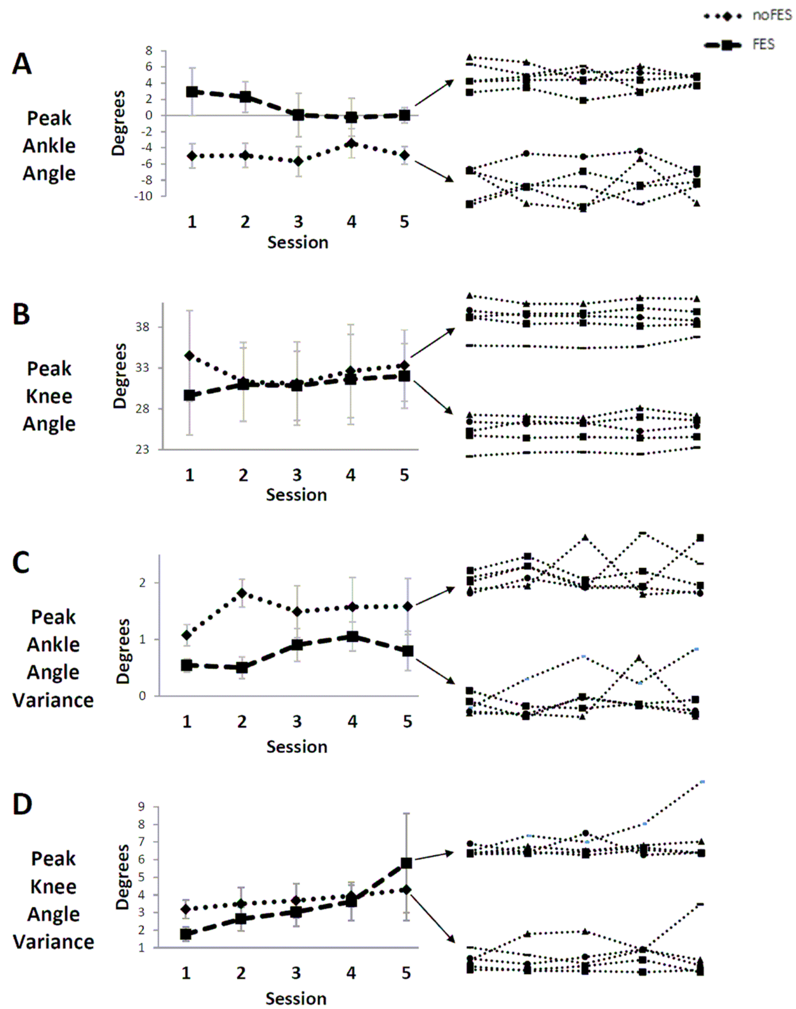

Figure 2.
presents the mean values (left) and corresponding individual subject data (right, indicated by arrows) for peak ankle and knee angles (panels A and B) and variances (panels C and D) for the 5-session group (N=5). Each panel (A–D) presents across-session changes for both the FES and noFES conditions. For the individual subject graphs, each subject is given a unique symbol.
†† denotes a change greater than the known MDC.

Table 1

Subject characteristics.

Subject	Gender	Age (yrs)	Time Since Stroke Onset (yrs)	Side of Hemiparesis	Gait Speed (m/s)	Fugl Meyer (score)	Lesion
S 36	F	58	21.3	L	0.2	23	R CVA
S 37	F	51	1.9	L	0.3	20	R CVA
S 53	M	72	6.1	R	0.5	18	L CVA
S 38	M	58	9.9	R	0.7	21	L CVA
S 39	M	60	5.8	R	0.8	25	L CVA
S 1	M	66	2.4	L	0.9	24	R CVA
S 15	M	52	6.3	L	0.6	20	R CVA
S 40	M	49	9.3	R	0.9	28	R CVA
S 67	M	57	2.7	R	0.7	22	L CVA
Average		*58.1*	*7.3*		*0.6*	*22.3*	
Stdev		*7.3*	*6.0*		*0.2*	*3.0*	