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Rate of isometric knee extension strength development and walking speed after stroke

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Abstract—The relationship between lower-limb weakness and walking speed after stroke is not clear. This may be related to the measurement used to quantify weakness, typically peak strength. This study examined the relationship between two measures of isometric knee extension strength, i.e., peak torque and the rate of torque development and walking speed in adults with stroke. This study had 83 stroke survivors who participated. For the affected lower limb, rate and peak torque explained 12% of the variance in gait speed. Removing rate from the model significantly reduced the explained variance; in contrast, removing peak torque did not reduce the variance. For the less affected lower limb, rate tended to be more predictive of gait speed than peak torque. Diminished ability to rapidly generate knee extension torque contributes more to decreased walking speed after stroke than does maximal strength. Of note, 88% of the variance in gait speed is not explained by rate and peak isometric knee extension strength. Further studies are needed to determine if rehabilitation poststroke can increase the rate of knee strength development and if it results in faster walking speeds.

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INTRODUCTION

Muscle weakness on the side of the body contralateral to the side of the brain lesion, i.e., the affected side, is a characteristic of stroke. The efficacy of measuring and treating muscle weakness after stroke has been controversial because of the concomitant presence of spasticity and abnormal reflexes (see Bohannon for a review) [1]. Testing of muscle strength in adults poststroke, however, is reliable, and the importance of strength training after stroke has been acknowledged [2–4].

Muscle weakness is measured traditionally with the use of a manual muscle test, a 6-point ordinal scale that ranges from no strength to normal strength. With the increasing availability of sophisticated computer interfaced equipment, weakness may be quantified more precisely. The isokinetic dynamometer is used for isometric and isokinetic testing in stroke survivors [2,5–11]. With the isokinetic dynamometer, the tester can capture time history-related characteristics of force output in addition to absolute force output.

Strength measured with a dynamometer can be quantified in different ways. Peak torque obtained from a maximal voluntary contraction (MVC) during an isometric test is a common measure of strength. For example, in adults with stroke, isometric peak torques of the affected lower limb have been shown to be smaller than the less

affected lower limb [12]. Strength can also be quantified by one examining the rate of development. For example, in isometric testing of knee extension of the affected lower limb of adults with stroke, the time to peak torque and the time to 90 percent of peak torque were compared to gait speed; poor correlations were found [2]. These temporal measures may describe some functional control beyond that of an MVC, but they still relate to peak, or near peak, torques.

The strength demands of many functional skills, including walking, are far from maximal. Further, the temporal constraints of muscle torque development for walking suggest that the ability to generate torque within a physiologically meaningful time window is important. For knee extension, vastus activity begins in terminal swing and rapidly increases to a peak early in loading response, requiring force to be generated within about 150 ms [13]. A measure with these temporal constraints may be more relevant than peak torque achievable in an unconstrained time window.

The present study examines the relationship between two measures of isometric strength, peak torque, and the rate of torque development in the first 150 ms of effort, to walking speed in adults with stroke. We hypothesized that the rate of torque development would more likely predict walking speed than peak torque.

METHOD

Subjects

There were 83 stroke survivors who participated in this study. These individuals were part of a larger randomized clinical trial of a therapist-supervised 12-week therapeutic exercise program delivered in the home [14]. Subjects for the clinical trial were recruited from the Kansas City Stroke Registry, a registry of adults who were recruited within the first 28 days after their stroke (principal investigator, S. Lai, PhD). To be included in the registry, subjects had to be older than 50 years of age, reside within 60 miles of an inpatient hospital in the greater Kansas City area, and have suffered an ischemic or hemorrhagic stroke.

To enter the clinical trial, subjects were required to have been independent in basic activities of daily living before their stroke. Subjects were included only if they were free of major medical complications poststroke, such as a myocardial infarction or a second stroke. They had to be able to walk for 25 ft without supervision, with or without an assistive device. Subjects were excluded from the clinical trial if they had a comorbid condition that would prevent their participation in a home-based intervention that included strengthening, balance, and endurance training. Subjects who used oxygen at home for 24 hours a day were also excluded from the clinical trial. A combined Fugl-Meyer upper- and lower-limb motor score between 27 and 90 was required [15].

A Mini-Mental Status Examination score of 16 or greater out of a possible 30 was required as part of the parent study to accept self-reported data [16]. Subjects were excluded if any of the following applied:

- Medical condition that would interfere with outcomes assessments or limit participation in a submaximal endurance exercise program.
- Major receptive aphasia and/or inability to follow a two-step command.
- Life expectancy less than 1 year.
- Coma.
- Obtunded.
- Poorly controlled diabetes.
- Amputation.
- Legal blindness.
- Diagnosis of a progressive neurological disease.
- Current participation in inpatient rehabilitation.

Procedure

Before entering the registry and before entering the clinical trial, each subject provided oral and written informed consent. To continue in the study, subjects first had to participate in a bicycle ergometry stress test and be cleared by a cardiologist. After the stress test, subjects returned to the medical center within a week to complete a battery of laboratory and clinical performance testing and questionnaires for baseline assessment. Total testing time was 4 to 6 hours, with a lunch break provided.

Walking Speed

A walk test consisting of two successive 10 m walks without a rest in between was the first test given in the day. Subjects wore their own shoes except when their shoes had a heel-height greater than one-half inch; in which case, they were provided with canvas tennis shoes. Subjects were instructed to walk at a comfortable pace with any assistive device or orthotic they would typically use to walk down a hall.

Strength

Strength testing was conducted on a Cybex 6000 Dynamometer. Strength was evaluated at both the ankle (dorsiflexion) and knee (extension), on both sides of the body. Each subject wore canvas shoes for testing. Testing began with the less affected lower limb, followed immediately by the affected lower limb. For each motion and for each lower limb, isometric testing was followed by isokinetic testing. This paper reports only data from isometric testing of knee extension.

To test knee extension, we had the subject sit upright (85° from horizontal). The lower leg was strapped to the Cybex knee testing apparatus so that the shin pad fell 4 to 6 in. distal to the patella. The upper leg and torso were stabilized with Velcro straps and a safety belt. Subjects were told to relax the opposite lower limb and rest their hands in their lap. The subject was required to exert a torque against the fixed dynamometer in a single direction. Each joint was fixed at a specific angle (10° plantarflexion at the ankle, 60° flexion at the knee). A custombuilt trigger containing two lights and a buzzer was used to start each trial. The first light was a warning signal and indicated that the trial was starting; the subject was instructed to relax while this light was on (1,000 ms). The warning signal was incorporated to allow the subject to respond as fast as possible to the start signal by providing the subject with a precisely timed interval to prepare to detect the start signal [17]. The second light, which was illuminated simultaneously with the buzzer sounding, indicated that data collection was starting. Subjects were instructed that when they saw the light and heard the buzzer, they should perform the desired activity (i.e., knee extension) as quickly and as forcefully as possible until the examiner told them to stop. Data were collected for 5 s.

For each motion on each side, the subject was given a single practice trial, followed by three test trials. Rests were provided as necessary.

Data Processing

Torque and angle data were collected at 1,000 Hz as raw voltage signals from the Cybex and collected via an AMUX-64T multiplexer connected to an AT-MIO-16E-10 A/D board (National Instruments), with the use of a LabVIEW 6i interface. Data were processed with a custom MATLAB routine. Each trial consisted of a baseline "rest" period of at least 1 s followed by an MVC, for a total of 6 s of data. Before trials were accepted during data collection, each trial was visually screened for problems. The most typical problems were early initiation of the contraction ("jumping the gun"), early termination, sporadic relaxation, and contracting in the wrong direction. These trials were repeated immediately. To attain a full complement of six trials (three trials for each side), we required subjects on the average to perform one additional trial. Before processing, each trial was again screened for segments of decreasing torque, lasting longer than 50 ms during the initial build-up phase when torque was expected to be monotonically increasing. Trials with these dips were excluded from analysis. Of the total number of trials possible, 25 percent were excluded. The excluded trials were distributed so that there were only 18 instances (11 percent) in which there was no acceptable trial for a subject on a given side.

Data were smoothed with a 20-point averaging algorithm, which was repeated three times. Data were then zero-meaned based on the rest period data (**Figure 1**). Baseline mean and standard deviation (SD) values were calculated for the rest period, and the point of MVC initiation was determined as the first point that exceeded the mean plus one standard deviation. Window length for calculating the rate of torque development was based on relevant neurophysiological data from gait as to the time available for muscle contraction during the normal gait cycle; a window of 150 ms was selected for knee extension (see Introduction).

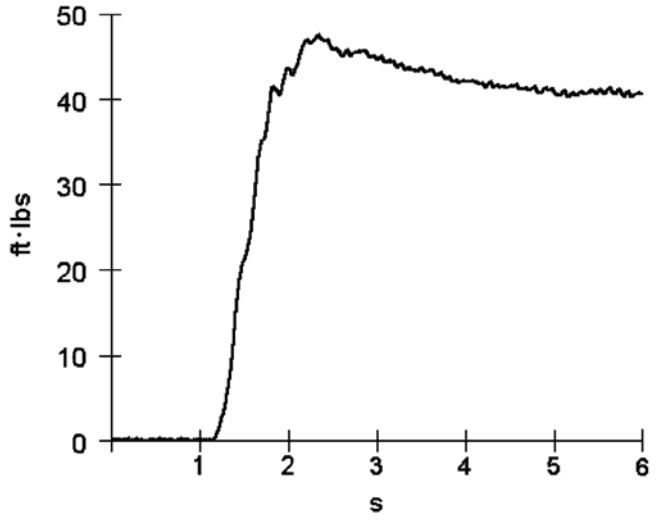

Figure 1.
Processed torque output over a 6 s trial from a subject using less affected lower limb.

Data within this window immediately after MVC initiation were fit linearly, and the slope of this linear fit was evaluated as the rate of torque development (**Figure 2**). The only exceptions to these actions were trials in which a relative peak torque was achieved before the end of the window. For these trials, the window was first resized to begin at MVC initiation and to end at the relative peak.

Data Analysis

Using the rate of torque development and peak torque for each of the three trials, means were calculated for the affected and less affected limbs. A regression analysis was done for each limb with the variables of rate, peak, age, and gender. This provided the total variance (R^2) of walking speed that was explained by these four variables for each limb. To test our hypothesis that the rate of torque development is more predictive of walking speed than peak torque, we calculated the changes in the R^2 by removing the rate or peak for the affected and less affected limbs.

RESULTS

The mean age of the 83 adults in this study was 70.3 ± 9.8 years with a range of 50 to 90 years. Thirty-nine were female and forty-four were male. The side of brain damage was in the right hemisphere for 45 subjects and in the left hemisphere for 38 subjects. With the use of the Orpington Scale to rate severity of stroke at the time of admission into the Stroke Registry, 23 subjects had a minor stroke, 53 a moderate stroke, and 2 a severe stroke [18]. At the time of the baseline testing for this study, subjects were 78.6 ± 27.4 days poststroke onset, with a arange of 36 to 145 days. The average Mini-Mental Status Examination score was 26.4 ± 5.3. Out of a possible 34 on the lower-limb motor portion of the Fugl-Meyer Assessment, the average score of these subjects on the day of baseline testing was 23.7 ± 3.7. Although the presence of neglect or apraxia was not an exclusion criterion for entrance to the study, none of the subjects demonstrated profound neglect or praxis that limited their ability to perform the baseline testing for the study.

The average walking speed during the 10 m walk was 63.2 ± 25.9 cm/s. Speeds ranged from 14.7 cm/s to 118.6 cm/s. During the walking trial, 57 subjects used an assistive device and the remaining 26 did not use an assistive device. Only 15 subjects walked with an ankle-foot orthosis. Strength data are summarized in **Table 1**.

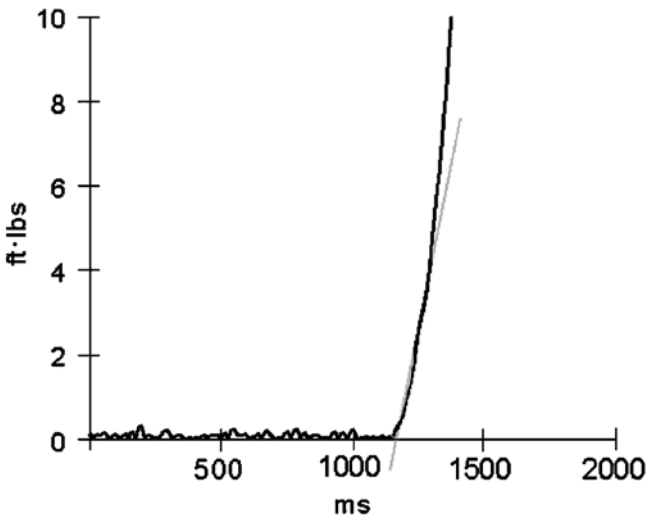

Figure 2.
First 2 s of trial from **Figure 1**. Straight gray line that intersects *x*-axis represents linear fit used to define rate of torque development.

Regression Models

The results for the regression models are presented in **Table 2**.

Affected Knee

Adjusting for age and gender, 12 percent of the variance in walking speed was explained by the rate of torque development and the peak torque. The removal of the rate from the model with age, gender, and peak significantly ($p = 0.0229$) reduced the R^2. In comparison, the removal of peak from the model did not reduce the R^2, regardless of the combination of variables in the model.

Less Affected Knee

Adjusting for age and gender, 10 percent of the variance in walking speed was explained by the rate and peak of torque. There was a significant ($p = 0.0466$) reduction

Table 1.
Isometric strength for knee extension.

Variable		Affected	Less Affected
Slope (ft•lb/s)	Average	48.7 ± 51.2	60.3 ± 56.8
	Range	4.7 – 275.6	8.9 – 274.1
Peak (ft•lb)	Average	39.5 ± 17.9	3.9 ± 18.9
	Range	10.0 – 89.2	15.5 – 111.5

Table 2.
Results of regression analyses for affected and unaffected knee extension.

Variables in Each Model	$R2$	Reduction in R^2 Following Removal of Rate of Torque Development (p Value)	Reduction in R Following Removal of Peak Torque (p Value)
Affected Knee			
Age, Gender, Rate, Peak	0.12	0.06 (0.0229)	0.00 (0.8752)
Age, Rate, Peak	0.12	0.06 (0.0228)	0.00 (0.7119)
Gender, Rate, Peak	0.06	0.05 (0.0385)	0.00 (0.8728)
Rate, Peak	0.06	0.05 (0.0382)	0.00 (0.7278)
Less Affected Knee			
Age, Gender, Rate, Peak	0.10	0.04 (0.0620)	0.00 (0.7443)
Age, Rate, Peak	0.10	0.04 (0.0685)	0.00 (0.9525)
Gender, Rate, Peak	0.08	0.05 (0.0466)	0.00 (0.4368)
Rate, Peak	0.07	0.04 (0.0538)	0.00 (0.6445)

in the R^2 with the removal of rate from the model with rate, gender, and peak. In contrast, the removal of peak torque from any of the models did not significantly reduce the R^2.

DISCUSSION

In support of our hypothesis, the results of this study revealed that the rate of development of isometric torque of knee extension of the affected lower limb predicted walking speed more than the corresponding measure of peak torque. This was also true, to some extent, for knee extension of the less affected lower limb. These findings suggest that the rate of torque development, particularly for the initial 150 ms of knee extension, may be more important than peak torque for walking speed for stroke survivors. While the importance of strengthening after stroke is now acknowledged, our results suggest that functional measures of strength and subsequent training efforts should be concerned with how fast torque can be generated and not just the absolute amount of torque that can be generated.

This study compared peak torque and the rate of torque development and their relationship to walking speed. We did not anticipate that these two measures would explain most of the variability in walking speed.

In fact, our results revealed that 88 percent of the variability in walking speed was not explained by either measure of isometric strength. Strength is an important but not comprehensive determinant of gait. Perry stated that the impairments that alter walking include deformity, muscle weakness, impaired control, and pain [13, p. 171]. Further, isolated testing of muscle performance may not reflect the nature of a continuous, cyclical activity such as walking. In older adults, rapid repetitive movements are more susceptible to impairments than a single isometric contraction [19]. Thus, strength as measured by unidirectional isometric contractions cannot capture all the control requirements of walking.

Muscle weakness, however, does contribute to functional limitations experienced by stroke survivors. Weakness after stroke is correlated to mobility scores of the Functional Independence Measure and gait speed [2,5,6,20–22]. The strength of knee extension predicts community ambulation after stroke [23]. Even in the acute stages of stroke, strength has an important relationship to function. The appearance of lower-limb strength within the first week after stroke in the previously paralyzed lower limb predicts the ability to regain walking ability; those who did not increase strength, as measured by a 7-point ordinal scale, remained nonambulatory [24].

Restricting considerations of the relationship of function and strength to peak torque may not adequately describe the control needed for daily activities. Many functional activities do not require the maximal levels of force quantified by peak torque. The relationship between muscle strength and functional skills has been described as a curvilinear relationship [25]. There is a threshold where strength is sufficient to perform the activity; additional gains in strength will not lead to gains in functional status.

The lack of a linear relationship between strength and function likely contributes to the discrepancies in the

literature regarding the correlation between peak torque of lower-limb musculature and gait speed after stroke. Reports show that peak torque measurements of the affected lower limb are related to gait speed after stroke [5–7,26,27]. Others have reported that no correlation was found between isometric peak torque of the affected knee extensors and gait velocity [28]. Peak torque of the less affected lower limb is correlated to gait speed [2,5], although not predictive of gait speed [26]. Time to peak isometric torque of the less affected knee extensors is correlated to gait speed [2]. It is acknowledged that strength deficits, as indicated by an MVC, have not always been found on the less affected lower limb of adults poststroke when compared to controls [8].

In a study that included an analysis of rate of isometric torque development for knee extension, individuals with stroke took approximately 1330 ms to generate peak torque with the affected lower limb and approximately 1180 ms with the less affected lower limb. The times to 90 percent peak torque were less; 680 ms for the affected lower limb and 520 ms for the less affected lower limb [2]. Regardless, the times are well beyond the temporal demands of rapid force development required in walking. The results of our study extend these findings, demonstrating that the ability of adults with stroke to generate even minimal knee extension force over the first 150 ms of effort is compromised.

Improvements in absolute strength of the affected lower limb have been realized as a result of various training programs for stroke survivors [10,11]. However, a lack of evidence exists supporting the relationship between strength gains after stroke and improvements in walking ability. It is not known whether the rate of torque development can be improved after stroke and whether or not improvements will be related to functional gains. The rate of isokinetic torque development of the hamstrings improved in adults with stroke who participated in a treadmill training program [10]. A direct comparison of the improvement in rate, however, to changes in walking speed was not made. Further studies are needed to inform clinicians about the efficacy and, if efficacious, the design of treatments that will produce meaningful changes in the rate of strength development for stroke survivors.

Results of this study cannot be applied to all adults poststroke. Our strict criteria for participation in the randomized clinical trial restrict the generalizability of our results. Our subjects ranged from 50 to 90 years of age. Age-related changes in strength have been documented [29]. The greatest amounts of variance for the lower limb were explained when age was included in the model. Further studies are needed to understand the relationship between age, the rate of isometric torque development, and walking speed. Our strength data were restricted to knee extension. Other lower-limb muscles groups (i.e., hip flexors) have been shown to have a strong effect on gait speed [27]. It is not known whether the rate of torque development is more predictive than peak torque for lower-limb muscle groups other than the knee extensors.

CONCLUSION

We present evidence that the rate of torque development over the first 150 ms of knee extension helps predict walking speed after stroke more than the peak torque. Further studies are needed to determine whether rehabilitation programs to enhance the rate of strength development in the lower limbs are effective in improving ambulatory function after stroke.

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