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The need for speed: Better movement quality during faster task performance after stroke

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1 **ABSTRACT**

2 **Background:** Although slow and insufficient muscle activation is a hallmark of hemiparesis
3 post-stroke, movement speed is rarely emphasized during upper extremity rehabilitation.
4 Moving faster may increase intensity of task-specific training, but positive and/or negative
5 effects on paretic-limb movement quality are unknown. **Objective:** To determine whether
6 moving quickly instead of at a preferred speed either enhances or impairs paretic limb task
7 performance after stroke. **Methods:** Sixteen people with post-stroke hemiparesis and 11 healthy
8 controls performed reach-grasp-lift movements at their preferred speed and as fast as possible,
9 using palmar and 3-finger grip types. We measured durations of the reach and grasp phases,
10 straightness of the reach path, thumb-index finger separation (aperture), efficiency of finger
11 movement, and grip force. **Results:** As expected, reach and grasp phase durations decreased in
12 the fast condition in both groups, showing that participants were able to move more quickly
13 when asked. When moving fast, the hemiparetic group had reach durations equal to those of
14 healthy controls moving at their preferred speed. Movement quality also improved. Reach paths
15 were straighter and peak apertures were greater in both groups in the fast condition. The group
16 with hemiparesis also showed improved efficiency of finger movement. Differences in peak grip
17 force across speed conditions did not reach significance. **Conclusions:** People with hemiparesis
18 are able to move faster than they choose to, and when they do, movement quality is improved.
19 Simple instructions to move faster could be a cost-free and effective means of increasing
20 rehabilitation intensity after stroke.

21

22 **Keywords:** hemiparesis, speed, kinematics, upper extremity, motor control, reach-to-grasp

23

1 **INTRODUCTION**

2 The neurological system is known to be highly adaptable and capable of transforming
3 functionally and structurally after injury, in a use-dependent manner¹⁻⁴. Clinicians and
4 researchers alike now seek to identify the parameters of physical training that maximize neural
5 adaptation and allow individuals to approach their potential in terms of motor control and
6 function. Repetitive task-specific training is a key stimulus to promote neural adaptation and
7 recovery after stroke⁵⁻⁸. Implementation of task-specific training for the upper extremity remains
8 challenging for clinicians, however, given the multitude of choices regarding what to practice
9 and specifically how to practice⁹.

10 Stroke disrupts the sensorimotor neural network that governs movement, causing slow
11 and often insufficient muscle activation¹⁰⁻¹⁴. Although this leads to slow, awkward movement¹⁵,
12 speed of task performance during training is rarely emphasized in either clinical or experimental
13 intervention protocols¹⁶⁻¹⁸. Reasons for this are unclear, but may stem from traditional
14 therapeutic approaches where the focus was on minimizing hyperactive stretch reflexes and
15 abnormal movements in order to promote better movement quality¹⁹. More currently,
16 principles of neuroplasticity now suggest that kinematic, kinetic and temporal characteristics of
17 movement should be optimized during practice, in order to produce appropriate task-specific
18 sensory feedback that contributes to reshaping of the sensorimotor neural network²⁰.

19 Intensity of upper extremity rehabilitation post-stroke is often insufficient, as revealed by
20 the many clinical trials that show less improvement after standard care compared to experimental
21 training protocols that increase intensity by adding training time²¹⁻²⁴. We suggest that intensity
22 can also be enhanced by increasing the speed of task performance during training. Instructions
23 to move faster could increase intensity by encouraging more effortful practice, and by allowing

1 more repetitions of task practice to be performed within the time allotted for each therapy
2 session. A first step in evaluating whether speed-intensive practice may enhance rehabilitation
3 outcomes is to test for effects of movement speed on task performance within a single session.

4 Only two studies have questioned the effects of movement speed on upper extremity task
5 performance after stroke. In one, faster paretic limb movements were associated with increased
6 opening of the hand, and a smaller percentage of the reaching movement was spent decelerating
7 as the hand approached the object to be grasped²⁵. In another study, non-paretic limb reaching
8 trajectories were smoother (i.e. they included fewer acceleration/deceleration reversals), when
9 speed was emphasized over accuracy²⁶. Similar speed-related changes in motor performance
10 have been demonstrated in healthy participants²⁷⁻²⁹ and people with other movement disorders³⁰,
11 but have not been adequately investigated in the paretic limb of people post-stroke.

12 The purpose of this study, therefore, was to determine whether moving quickly instead of
13 at a preferred speed either enhances or impairs performance of a reach-grasp-lift task by the
14 paretic limb of people with post-stroke hemiparesis. Based on previous findings²⁵, we expected
15 that participants would be able to increase their movement speed when asked. We hypothesized
16 that faster movements would be associated with improved movement quality, as measured by
17 reach path straightness, thumb-finger separation (aperture), smoothness of thumb-finger opening
18 and closing, and grip force. If faster speeds benefit performance without negative consequences,
19 simple instructions to move faster could be a cost-free and effective means of increasing
20 intensity and maximizing the therapeutic dose of activity contained within each therapy session.

21

22 **METHODS**

23 **Participants**

1 Sixteen people with hemiparesis due to stroke were recruited from the St. Louis
2 metropolitan area via the Brain Recovery Core Database and the Cognitive Rehabilitation
3 Research Group Stroke Registry at Washington University, and from local support groups for
4 people with stroke. Potential participants were included if they 1) had a recent diagnosis of
5 ischemic or hemorrhagic stroke by a stroke neurologist, 2) had persistent hemiparesis, as
6 evidenced by upper extremity Medical Research Council muscle test scores that were at least one
7 muscle grade lower on the paretic side compared to the non-paretic side, 3) were able to reach,
8 grasp and lift a vertical cylinder (3.4 cm diameter, 420 grams) using palmar and 3-finger grip
9 types, as necessary to complete the study procedures, and 4) had the ability to follow 2-step
10 commands. We excluded people who 1) had severe aphasia as indicated by a score of 2 or 3 on
11 the Best Language item of the National Institutes of Health Stroke Scale (NIHSS), 2) had severe
12 hemispatial neglect, as indicated by a score of 2 on the Extinction and Inattention item on the
13 NIHSS, 3) had musculoskeletal or other medical conditions besides stroke that limited either
14 upper extremity, or 4) were unable to give informed consent.

15 For comparison, eleven healthy adults were recruited from the Volunteer for Health
16 Research Participant Registry at Washington University. Volunteers were included if they 1)
17 were at least 30 years old, 2) had no known neurological disease, and 3) had no disability or
18 injury affecting their upper extremity on either side. To evenly represent both genders across the
19 age range, we recruited one male and one female within each decade between 30 and 79 years of
20 age. One 81 year-old male also volunteered. This study was approved by the Washington
21 University Human Research Protection Office, and all participants provided informed consent
22 prior to beginning the study.

23

1 **Clinical Assessments**

2 Clinical tests were used to describe the participants with post-stroke hemiparesis (Table 1). We
3 assessed upper extremity function using the Action Research Arm Test (ARAT) on the paretic
4 side³¹⁻³³ and the Activities of Daily Living and Hand Function domains of the Stroke Impact
5 Scale, version 3.0^{34,35} (SIS). Maximum grip strength was measured on each side using a Jamar
6 grip dynamometer^{36,37}. Maximum pinch strength was measured on each side with a Jamar
7 hydraulic pinch gauge positioned between the thumb and the lateral side of the index finger's
8 middle phalanx^{38,39}. Sensation on the palmar surface of the distal index finger was evaluated
9 using Semmes-Weinstein monofilaments⁴⁰. Spasticity of the elbow flexors was assessed on the
10 paretic side using the Modified Ashworth Scale⁴¹.

11

12 **Experimental Procedures**

13 For each participant, data collection was completed in a single session. Upper extremity
14 movement and grip force were measured during reach-grasp-lift movements in preferred speed
15 and fast conditions using palmar and 3-finger grip types. These grip types were chosen because
16 they have been well characterized as two discrete patterns of prehension with different levels of
17 accuracy and precision, and because they represent a range of actions observed in daily life⁴²⁻⁴⁵.
18 The object that was grasped consisted of a custom-fabricated vertical cylinder (34 mm diameter,
19 113 mm height) attached to a rectangular base (135 by 60 mm) that was designed to hold a
20 Tekscan I-scan electronic interface (Tekscan, Inc. South Boston, MA). The cylindrical portion
21 of the object was covered with a Tekscan pressure sensor (112 by 112 mm, 1936 sensels, spatial
22 resolution 155 sensels/mm²). Combined weight of the object and electronics was 420 grams.
23 Pressure data were collected at 100 Hz. Measurement of grip force is a novel use of pressure

1 sensor technology⁴⁶. Although previous studies of grip force control in people with stroke have
2 used custom-made devices equipped with strain gauges^{47, 48}, we chose to use a pressure sensor
3 because it does not require that participants place their hand or fingers on specific locations.
4 Instead, each participant's natural grasping performance was measured by the pressure sensor,
5 which covered the entire surface of the vertical cylinder⁴⁶. Using this method, we determined
6 precisely when the hand contacted the object, and quantified grip force applied to the object. A
7 disadvantage of the pressure sensor system is that it only measures grip forces (normal forces)
8 and is unable to measure load forces (tangential or shear forces). For use in this study, we
9 believed that the advantage of capturing natural movements outweighed the disadvantage of
10 limiting our force analysis to grip (i.e. normal) forces.

11 We tested the contralesional, paretic upper extremity of participants with hemiparesis,
12 and one randomly selected side for control participants. Three-dimensional movements of the
13 tested upper extremity and the grasped object were recorded at 50 Hz using an electromagnetic
14 tracking system (The MotionMonitor, Innovative Sports Training, Chicago, IL), capable of
15 determining sensor positions to within 1.8 mm (root mean square accuracy, per manufacturer
16 specifications). Nine sensors were attached to the trunk and upper extremity, as follows: 1)
17 trunk: midline below the sternal notch, 2) upper arm: proximal to the lateral epicondyle,
18 bisecting the upper arm mass, 3) forearm: midpoint between the radial and ulnar styloids on the
19 dorsum of the forearm, 4) hand: midpoint of the third metacarpal on the dorsum of the hand, and
20 5 through 9) thumb and fingers: on the nail of each digit. The instrumentation produced minimal
21 interference with reaching, grasping and lifting movements, since all sensors on the hand and
22 forearm were placed dorsally, and since all leads were supported using wraps at the forearm and
23 upper arm. In each session, after all sensors were applied, all upper extremity joints were moved

1 through their available range of motion, to ensure that the leads did not restrict movement. One
2 additional sensor was attached at the base of the cylindrical object, so that its vertical position
3 could be used to determine precisely when the object was lifted.

4 As shown in Figure 1, participants were seated in a chair with back support for all data
5 collection. A table was placed with its closest edge across the participant's mid-thighs and the
6 height was adjusted to be as low as possible without contacting the thighs, in order to allow
7 clearance of the table edge while reaching. The object was placed on the table at a standardized
8 horizontal distance from the participant's shoulder (90% of the length of the arm from shoulder
9 to wrist). In the frontal plane, the object was aligned with the mid-clavicle.

10 Four trial types were collected, each characterized by the preferred speed or fast
11 movement condition and by the type of grip (i.e. palmar preferred speed, palmar fast, 3-finger
12 preferred speed, and 3-finger fast). We collected preferred speed trials before fast trials in order
13 to accurately capture natural preferred speed performance before introducing speed-related
14 instructions that could bias all subsequent trials. Within each speed condition, we randomized
15 the order in which palmar and 3-finger trials were collected. Although we considered the reach-
16 grasp-lift task to be highly learned already, we recognized the potential for practice effects to
17 confound the effects of speed condition, and therefore included three practice trials at the
18 beginning of each data collection session, prior to recording any movements. Further, we tested
19 for practice effects within each speed condition statistically.

20 Prior to each trial, the participant was instructed to rest both hands in their lap with thumb
21 and fingers together, wait for the word 'go', then grasp and lift the object, hold it above the table
22 for about 5 seconds until the examiner said 'done', then put it down and return to the starting
23 position. No speed-related instructions were provided prior to preferred speed trials. Before

1 each fast trial, the participant was instructed to wait for the word ‘go’, then complete the reach-
 2 grasp-lift movement as fast as possible while still being able to complete the task. Verbal
 3 instruction and demonstration was also provided regarding grip type. Three trials of each type
 4 were recorded consecutively, with approximately 10 seconds of rest between trials.

6 **Analysis**

7 Pressure data were converted to grams of force, using Tekscan software to multiply
 8 recorded pressure by the sensor’s spatial area. After low-pass filtering of kinematic data at 6 Hz
 9 using a second-order Butterworth filter, sensor position data were extracted using
 10 MotionMonitor software (Innovative Sports Training, Chicago, IL). Subsequent analysis was
 11 then completed using custom software written in MATLAB (The MathWorks, Inc., Natick,
 12 MA).

13 Durations of movement phases were determined based on hand velocity, force on the
 14 object, and object position (Figure 1C). The reach phase began when velocity of the hand sensor
 15 first exceeded 5 mm/s, and ended when force on the object first exceeded 5 grams. Pre-lift delay
 16 began at the end of the reach, and ended when the vertical position of the object increased by 3
 17 mm from its initial value (ie. object lift-off). Pre-lift delay represents the time needed to
 18 establish a stable grip and begin the lifting movement. Movement quality was evaluated using
 19 the following variables:

- 20 ♦ **Reach path ratio** quantified curvature of the reach path, based on the forearm sensor’s
 21 three-dimensional trajectory. Reach path ratio was calculated by dividing the length of
 22 the forearm sensor’s actual path during the reach phase, by the length of a straight line
 23 path from the forearm sensor’s position at the start of the reach phase to its position at the

1 end of the reach phase⁴⁹. In healthy people, reach path ratios are typically close to one,
 2 indicating a straight, direct reach⁵⁰, achieved when the ratio of the shoulder and elbow
 3 angular velocities remains nearly constant throughout the reaching movement^{49, 51-53}.

4 Reach path ratios greater than one indicate curvature of the reach path, caused by reduced
 5 coordination of shoulder and elbow joint movements^{53, 54}.

6 ♦ **Peak aperture** quantified how far the hand opened. Aperture was defined as the three-
 7 dimensional distance between sensors on the thumbnail and the index fingernail. Note
 8 that because the sensors were placed on the fingernails, this measurement includes the
 9 thickness of the thumb and index fingertips. Peak aperture was the maximum aperture
 10 occurring in the reach phase.

11 ♦ **Aperture path ratio** quantified the efficiency of thumb and index finger movement
 12 during the reach phase, and was calculated as follows⁴⁶,

13
$$\text{Aperture Path Ratio} = \frac{\text{Sum of the absolute values of all changes in aperture during the reach phase}}{(\text{Peak aperture} - \text{aperture at beginning of reach}) + (\text{Peak aperture} - \text{aperture at end of reach})}$$

14
 15 This equation is based on the idea that efficient finger movements during reach-to-grasp
 16 are characterized by a single, direct opening to the point of peak aperture, followed by a
 17 single direct closing onto the object. The denominator in the above equation thus
 18 represents the most efficient aperture path, and the numerator represents the participant's
 19 actual aperture path. In healthy people, aperture path ratios are typically equal to one,
 20 indicating a single direct separation of the thumb and index finger to the maximum
 21 aperture value, followed by a single direct closing onto the object. Higher values indicate
 22 abnormal, inefficient opening and closing of the thumb and index fingers, typically seen

1 when participants make multiple attempts to open their hand and then close it on the
2 object.

3 ♦ **Peak grip force** was defined as the maximum force applied to the object, during an
4 interval beginning when the hand first contacted the object and ending one second after
5 the object was lifted off the table.

6 Reliability of kinematic reaching variables has been shown to be adequate in healthy
7 individuals and people with post-stroke hemiparesis⁵⁵⁻⁵⁷. In a recent evaluation of a reach-to-
8 grasp task similar to the task used in the current study, excellent reliability was reported for reach
9 duration, reach path ratio, and peak aperture ($r > 0.75$) in a group of people with hemiparesis
10 after stroke⁵⁶. Although these reliability studies used video-based motion capture systems
11 instead of the electromagnetic system we used, direct comparison supports similarity of results
12 obtained with the two motion analysis methods⁵⁸.

13 Variables were calculated separately for each trial. Each participant's performance in
14 each movement condition was represented by the mean of three trials. Kolmogorov-Smirnov
15 tests were used to determine whether data were normally distributed. Since all data met the
16 normality assumption ($p > 0.05$), parametric statistics were used. For each variable, we tested
17 for effects of trial order (i.e. practice effects) in each group by comparing the six trials performed
18 for each speed condition (three for each grip type) using repeated measures ANOVA. For each
19 variable, 2 x 2 x 2 mixed effects analysis of variance was used to determine effects of movement
20 condition (preferred speed vs. fast), grip type (3-finger vs. palmar), and group (control vs.
21 hemiparesis). Statistica software was used for normality testing and analysis of variance
22 (Version 6.1 Statsoft Inc., Tulsa, OK), and the criterion for significance was set at $p < 0.05$.
23 Effect sizes were calculated for statistically significant differences between speed conditions

1 using Hedges' g , which is equal to the mean difference between conditions divided by the pooled
2 unbiased standard deviation.

3

4 **RESULTS**

5 Characteristics of the 16 participants with hemiparesis are provided in Table 1. Time
6 since stroke ranged from two weeks to nine years, and was less than four months in all except
7 four participants. Severity of sensorimotor impairment and functional limitation ranged from
8 mild to moderate, as shown by the strength measures and scores on the ARAT and SIS
9 assessments. Eleven reported that they were right handed before their stroke, and five reported
10 being left handed.

11 Eleven healthy adults also participated, including five males and six females between 34
12 and 81 years of age (mean 55, SD 15 years). Nine were right handed and two were left handed,
13 by self report. Random selection of the side to be tested resulted in six rights and five lefts. The
14 dominant side was tested in six participants (five right-handed, one left-handed).

15 Group differences were not significant with respect to age (t-test, $p = 0.45$), gender
16 (Mann-Whitney U, $p = 0.64$), hand dominance (Mann-Whitney U, $p = 0.57$), or dominant/non-
17 dominant status of the tested side (Mann-Whitney U, $p = 0.54$).

18

19 **Effects of trial order**

20 In each group, comparison of the six trials within each speed condition (3 for each grip
21 type) revealed no significant effects of trial order on reach duration, pre-lift delay, reach path
22 ratio, peak aperture, aperture path ratio, or peak grip force (repeated measures ANOVA, $p >$
23 0.05).

1 **Effects of movement speed**

2 As expected, participants in both groups were able to move faster than their preferred
3 speed when asked (Figure 3). Means, standard errors, and differences between speed conditions
4 are presented in Table 2, with ANOVA results and effect sizes. Compared to the preferred speed
5 condition, reach duration (Figure 3A) was 40% shorter in the fast condition in the hemiparetic
6 group (post-hoc $p < 0.05$), and 47% shorter in the fast condition in the control group (post-hoc p
7 < 0.05). Within each speed condition, reach durations were longer in the hemiparetic group
8 compared to controls (post hoc $p < 0.05$). When moving fast, however, the hemiparetic group
9 showed reach durations equal to those of healthy controls moving at their preferred speed (post-
10 hoc $p = 0.93$). Compared to the preferred speed condition, pre-lift delay (Figure 3B) was 37%
11 shorter in the fast condition in the hemiparetic group (post-hoc $p < 0.05$), and 52% shorter in the
12 fast condition in the control group (post-hoc $p < 0.05$).

13 Improvements in movement quality were also evident during faster task performance.
14 Representative data from individual participants with hemiparesis and healthy controls are
15 shown in Figure 4. In the participant with hemiparesis, reach trajectories in the fast condition
16 were straighter than they were in the preferred speed condition (Figure 4A, left panel vs. middle
17 panel). Aperture path ratio was decreased (improved) in the fast condition compared to the
18 preferred speed condition, shown by smoother aperture traces (Figure 4B, left panel vs. middle
19 panel). When moving at preferred speed, the hemiparetic participants' performance differed
20 from that of the healthy controls moving at preferred speed (Figure 4, left panels vs. right
21 panels). When moving fast, however, hemiparetic participants' performance was similar to that
22 of the healthy controls moving at preferred speed (Figure 4, middle panels vs. right panels).

1 Group data for the measures of movement quality are shown in Figure 5. Means,
2 standard errors, and differences between speed conditions are presented in Table 2, with
3 ANOVA results and effect sizes. Both groups showed lower (better) reach path ratios and
4 greater peak apertures in the fast condition compared to the preferred speed condition (main
5 effect of speed, $p < 0.05$). In the hemiparetic group only, aperture path ratios were lower (better)
6 in the fast condition compared to the preferred speed condition (speed condition by group
7 interaction effect, $p < 0.05$, post hoc $p < 0.05$ for hemiparetic group only). Although the main
8 effect of movement speed on peak grip force approached significance ($p = 0.06$), post hoc testing
9 failed to find a difference between speed conditions in either group (hemiparetic group $p = 0.94$,
10 control group $p = 0.20$).

11 **Effects of group and grip type**

12 Some additional significant effects of group and grip type were also found (Table 2).
13 Pre-lift delays and reach path ratios were greater in the hemiparetic group than in controls (main
14 effects of group, $p < 0.05$, Figures 3B and 5A, respectively), regardless of speed condition (no
15 group x condition interactions). Differences between groups did not reach significance for
16 aperture path ratio, peak aperture, or grip force (Figures 5B, 5C, and 5D).

17 In the hemiparetic group only, reach duration and pre-lift delay were longer during 3-
18 finger grip trials compared to palmar grip trials (post-hoc $p < 0.05$). In both groups, peak
19 aperture and peak grip force were greater during palmar grip trials compared to 3-finger grip
20 trials (main effect of grip type $p < 0.05$). Grip type did not affect reach path ratios or aperture
21 path ratios significantly in either group.

22

23 **DISCUSSION**

1 **Faster is possible**

2 This study demonstrated that people with mild to moderate post-stroke hemiparesis are
3 able to increase their movement speed upon request, and when they do, movement quality is
4 improved. Reach paths are straighter, finger movements are more efficient, and the fingers open
5 wider. These measures of task performance are known to be altered after stroke and have the
6 potential for recovery^{59, 60}. As most of our participants were within a few months post-stroke,
7 our findings suggest that incorporating the fast movement condition into rehabilitation may
8 improve movement quality during training and thus potentially may contribute to improved
9 outcomes.

10 Shorter reach durations and pre-lift delays in the fast condition demonstrate that people
11 with hemiparesis can voluntarily move faster than their preferred speed and can approach the
12 movement speeds of healthy individuals. This is likely accomplished through earlier activation
13 of upper extremity muscles (quicker muscle onsets) and better modulation of muscle activity
14 (higher levels of activation), as has been shown to occur during recovery of reaching¹⁵. Slow
15 and insufficient muscle activation is a fundamental movement problem after stroke¹⁰⁻¹⁴, and
16 people with hemiparesis often choose to use their opposite limb instead when the paretic limb is
17 too slow or unreliable⁶¹. Aside from any potential improvements in movement quality, aiming to
18 increase paretic limb movement speed is itself a reasonable goal of upper extremity
19 rehabilitation.

20

21 **Faster is better**

22 This is the first study to demonstrate improved paretic-limb coordination during faster
23 movement, as shown by the reach path and aperture path ratios. These variables reflect the

1 efficiency of reach and grasp movements and have been shown to be related to upper extremity
2 function at various time points post stroke^{31, 59, 60}. For peak aperture, our results echo those of
3 van Vliet and Sheridan²⁵, who also showed wider finger opening during fast movements in
4 healthy controls and people post-stroke, and suggested that excessive aperture may be a
5 compensation for increased spatial variability during faster movement²⁵. Since larger peak
6 apertures were found at faster speeds in both groups (main effect of speed, figure 5C), this is
7 likely a normal compensation during fast movement, and not one that is due to movement
8 impairment post-stroke. It should be noted that even after accounting for the thickness of the
9 fingertips, peak apertures in both groups were substantially larger than the 34 mm diameter of
10 the target object. If larger apertures result in more reliable task completion, then this would be
11 functionally beneficial for people with stroke.

12 For the comparison across speeds in the hemiparetic group, effect sizes were medium for
13 aperture path ratio ($0.5 \leq g \leq 0.8$), small for reach path ratio ($0.3 \leq g \leq 0.5$), and minimal for peak
14 aperture ($g \leq 0.3$). No detrimental effects of the fast movement condition were observed. These
15 results imply that fast training has the potential to increase rates of muscle activation and
16 improve the spatiotemporal pattern of activation that controls proximal and distal multi-joint
17 movements. In addition, fast training may allow for more task repetitions during the same
18 allotted therapy time, as has been explored recently in a proof-of-concept trial⁶².

19 Although outcomes of fast training have not been examined in the upper extremity,
20 outcomes from fast gait training studies provide valuable insight. Simply informing people with
21 stroke of their fast walking speed each day during inpatient rehabilitation resulted in dramatic
22 improvements in walking speed⁶³. Likewise, when instructed to walk faster, people with stroke
23 show improved symmetry, increases in joint excursions and muscle activations, and less

1 compensatory paretic-limb circumduction⁶⁴. Cardiovascular fitness, walking endurance and
2 functional mobility have also been shown to increase much more after speed-intensive gait
3 training compared to a less intense protocol⁶⁵. The benefit of fast training may not be restricted
4 to one type of movement, but may extend to training of many functional movements.

6 **Limitations**

7 Recruitment into the hemiparetic group in this study was limited to a convenience sample
8 of people who were able to perform reach-grasp-lift movements with both palmar and 3-finger
9 grip types. Participants were, therefore, mildly to moderately impaired, and the results may not
10 generalize to people with more severe hemiparesis. People with mild to moderate impairments
11 post-stroke are most likely to benefit from task-specific training and are most likely to be
12 enrolled in stroke rehabilitation trials⁹. Our investigation was also limited to the within-session
13 effects of movement speed on kinematic and kinetic characteristics of task performance, and did
14 not explore training effects across multiple sessions. Further investigation into the feasibility,
15 safety, and potential benefits of incorporating the fast movement condition into task-specific
16 training appears warranted. It is possible that muscular, neurological, and/or cardiorespiratory
17 fatigue may limit implementation of fast task-specific training, particularly in certain individuals
18 with comorbidities. Lastly, the number of trials each participant performed in each condition
19 was limited to three, and the preferred speed trials were always performed first. While this order
20 of conditions was necessary so that instructions to move fast would not bias the preferred speed
21 trials, it leaves open the possibility that the results are due to practice effects. We consider this
22 possibility unlikely however, because the reach-grasp-lift task is an often used, highly learned

1 movement, because all participants had practice trials before the recorded ones, and because our
2 within-condition comparison of trial order failed to show any practice effects.

3

4 **Conclusions**

5 In summary, this study showed that people with mild to moderate hemiparesis post-stroke
6 are able to perform upper extremity reach-grasp-lift tasks substantially faster than their preferred
7 movement speed and, further, that movement quality is enhanced during faster movements. No
8 detrimental effects were observed in the fast condition. Simple instructions to move faster could
9 be a cost-free and effective means of increasing the intensity of task specific training after stroke.
10 Further studies of feasibility, safety and therapeutic effects are needed.

11

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16

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1 **FIGURE LEGENDS**

2 **Figure 1:** Assessment of task performance. Illustration of the experimental set-up and a
 3 participant beginning (A) and finishing (B) the reach-grasp-lift task with a 3-finger grip.

4

5 **Figure 2:** Example data from a healthy control participant performing one trial of the reach-
 6 grasp-lift task at preferred speed, using a 3-finger grip. Vertical dashed lines and solid black
 7 circles demonstrate division of the task into movement phases. The reach phase began when
 8 speed of the hand sensor first exceeded 5 mm/sec and ended when grip force first exceeded 5
 9 grams. Pre-lift delay began at the end of the reach and ended when the vertical position of the
 10 object increased by 3 mm from its initial value.

11

12 **Figure 3:** Comparison of phase durations in the preferred speed versus fast conditions. Values
 13 are means \pm 1 standard error. For healthy controls in the fast condition, some of the standard
 14 errors do not extend past the edges of the symbols (circles or triangles), and error bars therefore
 15 do not appear. Reach duration (A) and pre-lift delay (B) were shorter in the fast condition, in
 16 both groups. Reach duration was longer in the hemiparetic group compared to controls. When
 17 moving fast, however, the hemiparetic group had reach durations equal to that of the control
 18 group moving at preferred speed.

19

20 **Figure 4:** Examples of improved movement quality in the fast condition compared to the
 21 preferred speed condition in individual participants with hemiparesis. Trajectories of the
 22 forearm sensor in the sagittal plane (A), plotted from the start of movement (open circle), until
 23 the hand contacted the object. In one representative participant with hemiparesis, reach paths

1 were straighter during three fast trials (middle panel) compared to three preferred speed trials
2 (left panel). Aperture traces (B) plotted from the start of movement (0 msec) until the hand
3 contacted the object. In a different representative participant with hemiparesis, aperture traces
4 were smoother during three fast trials (middle panel) compared to three preferred speed trials
5 (left panel). In each example, performance of the participant with hemiparesis during three fast
6 trials (middle panels) approached that of a representative healthy control participant performing
7 three trials at preferred speed (right panels).

8

9 **Figure 5:** Comparison of movement quality in the preferred speed versus fast conditions. Both
10 groups showed lower reach path ratios (A) and greater peak apertures (C) in the fast condition
11 compared to the preferred speed condition. In the hemiparetic group only, aperture path ratios
12 were lower in the fast condition compared to the preferred speed condition (B). The standard
13 error for peak grip force in healthy controls in the preferred speed condition did not extend past
14 the edges of the symbol (triangle), and error bars therefore do not appear.

15

1 Table 1. Characteristics of participants with hemiparesis^a

2	Age, years	59 ± 11 (39 – 88)
3	Gender, n	
4	Male	9
5	Female	7
6	Paretic side, n	
7	Dominant	11
8	Non-dominant	5
9	Right	8
10	Left	8
11	Type of stroke	
12	Ischemic	14
13	Hemorrhagic	2
14	Time since stroke (median, range)	1.2 months (2 weeks – 9.4 years)
15	Grip strength	
16	paretic side in kg	21.9 ± 8.8 (10.0 – 36.0)
17	paretic side as % of non-paretic	69 ± 26 (37 – 112)
18	Pinch strength	
19	paretic side in kg	5.5 ± 1.9 (2.0 – 8.0)
20	paretic side as % of non-paretic	70 ± 21 (29 – 114)
21	Sensation ^b , n	
22	2.83	6
23	3.61	6
24	4.31	2
25	6.25	2
26	Spasticity ^c , n	
27	0	8
28	1	6
29	2	1
30	4	1
31	Action Research Arm Test ^d	41 ± 10 (20 – 53)
32	Stroke Impact Scale ^e	
33	Activities in a Typical Day	62 ± 15 (43 – 88)
34	Hand Function	50 ± 21 (0 – 85)

35
36 ^a Data are mean ± standard deviation (range), except where otherwise noted.

37 ^b Size of the smallest Semmes Weinstein monofilament sensed in 3 of 5 trials on the anterior distal index finger on
38 the paretic side

39 ^c Modified Ashworth Scale score for the elbow flexors on the paretic side

40 ^d Paretic side. Range of possible scores is 0 to 57, 57 = normal

41 ^e Range of possible scores is 0 to 100, 100 = normal

Table 2. Effects of movement speed on task performance^a

	Group	Palmar Grip			3-Finger Grip			Preferred vs. Fast Effect Size (g)
		Preferred Speed	Fast	Difference	Preferred Speed	Fast	Difference	
Reach Duration (msec) ^{b c d e f}	Hemiparesis	1279 ± 86	803 ± 60	-476 ± 79	1590 ± 139	913 ± 94	-677 ± 104	1.26
	Control	788 ± 80	423 ± 19	-365 ± 81	792 ± 50	417 ± 40	-375 ± 40	1.54
Pre-Lift Delay (msec) ^{b c d f}	Hemiparesis	659 ± 61	371 ± 23	-288 ± 64	790 ± 60	551 ± 58	-239 ± 80	1.24
	Control	588 ± 90	237 ± 15	-351 ± 86	562 ± 31	309 ± 29	-253 ± 49	1.51
Reach Path Ratio ^{b c}	Hemiparesis	1.37 ± 0.04	1.32 ± 0.04	-0.05 ± 0.03	1.35 ± 0.04	1.29 ± 0.04	-0.06 ± 0.03	0.37
	Control	1.23 ± 0.05	1.14 ± 0.03	-0.09 ± 0.03	1.18 ± 0.04	1.14 ± 0.05	-0.03 ± 0.03	0.48
Peak Aperture (mm) ^{c d}	Hemiparesis	118 ± 7	123 ± 7	6 ± 3	101 ± 7	108 ± 6	7 ± 4	0.24
	Control	120 ± 4	125 ± 3	5 ± 4	97 ± 3	106 ± 6	9 ± 6	0.62
Aperture Path Ratio ^{c e}	Hemiparesis	1.24 ± 0.07	1.14 ± 0.04	-0.10 ± 0.05	1.38 ± 0.07	1.15 ± 0.04	-0.22 ± 0.06	0.75
	Control	1.13 ± 0.04	1.14 ± 0.05	0.01 ± 0.03	1.12 ± 0.03	1.16 ± 0.07	0.04 ± 0.08	ns
Peak Grip Force (grams) ^d	Hemiparesis	3590 ± 436	4018 ± 491	428 ± 295	1942 ± 285	2013 ± 260	72 ± 68	ns
	Control	4062 ± 787	5566 ± 1781	1504 ± 1286	1162 ± 76	1644 ± 209	481 ± 217	ns

^aData are mean ± standard error. Negative numbers indicate lower values in the fast condition. Positive numbers indicate higher values in the fast condition.

^bMain effect of group, $p < 0.05$

^cMain effect of preferred vs. fast speed, $p < 0.05$

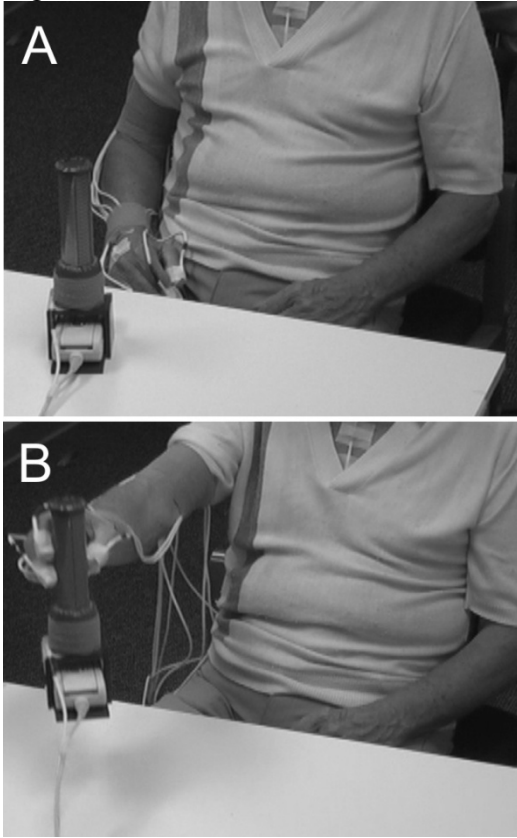
^dMain effect of grip, $p < 0.05$

^eSpeed x group interaction effect, $p < 0.05$

^fGrip x group interaction effect, $p < 0.05$

Effect sizes are reported for significant effects of speed condition in each group, collapsed across grip types. ns indicates no significant difference across speed conditions.

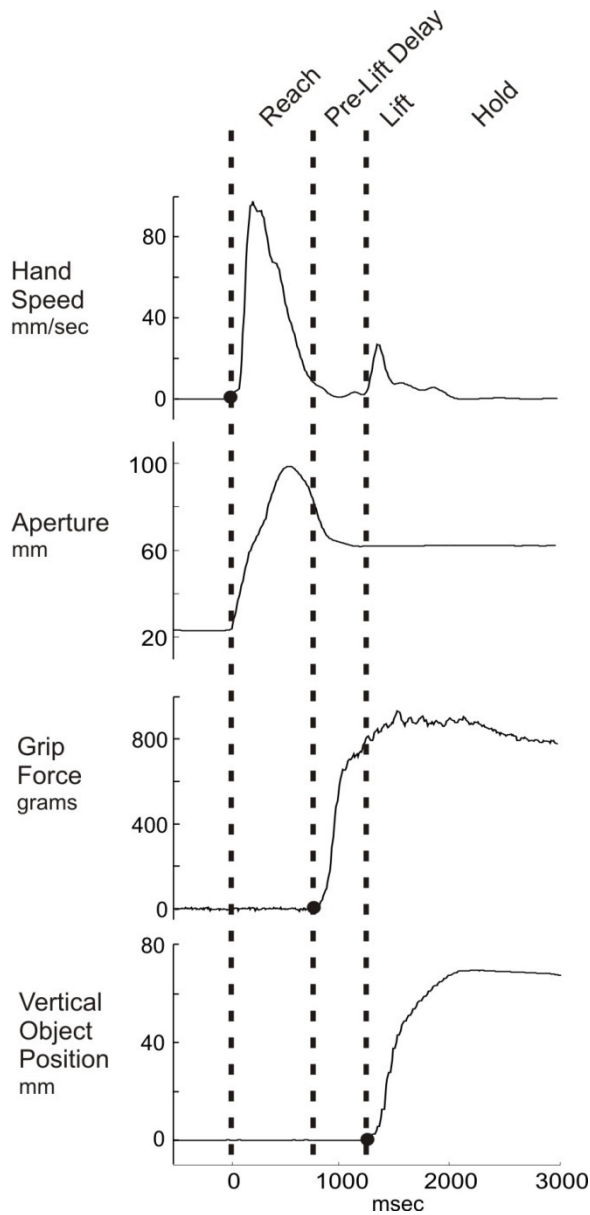
1 Figure 1



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Figure 1: Assessment of task performance. Illustration of the experimental set-up and a participant beginning (A) and finishing (B) the reach-grasp-lift task with a 3-finger grip.

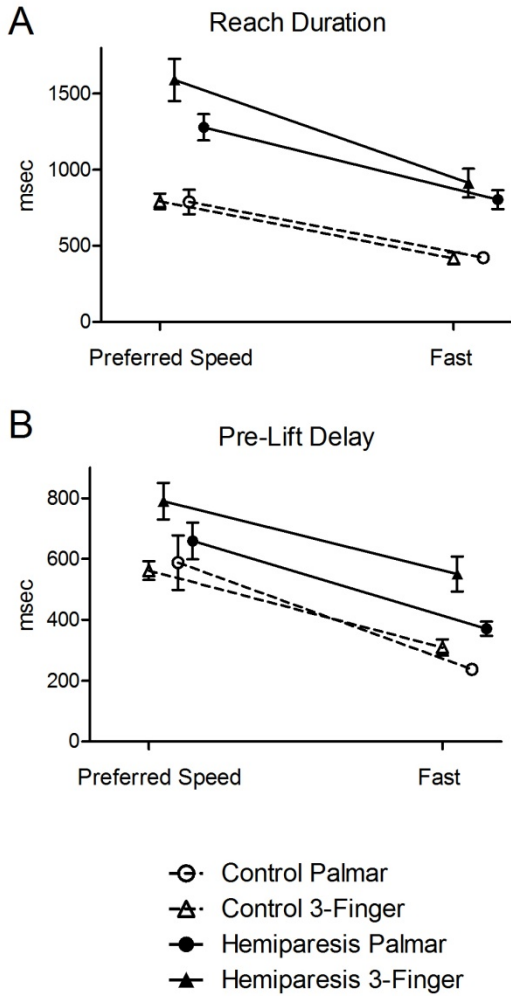
1 Figure 2
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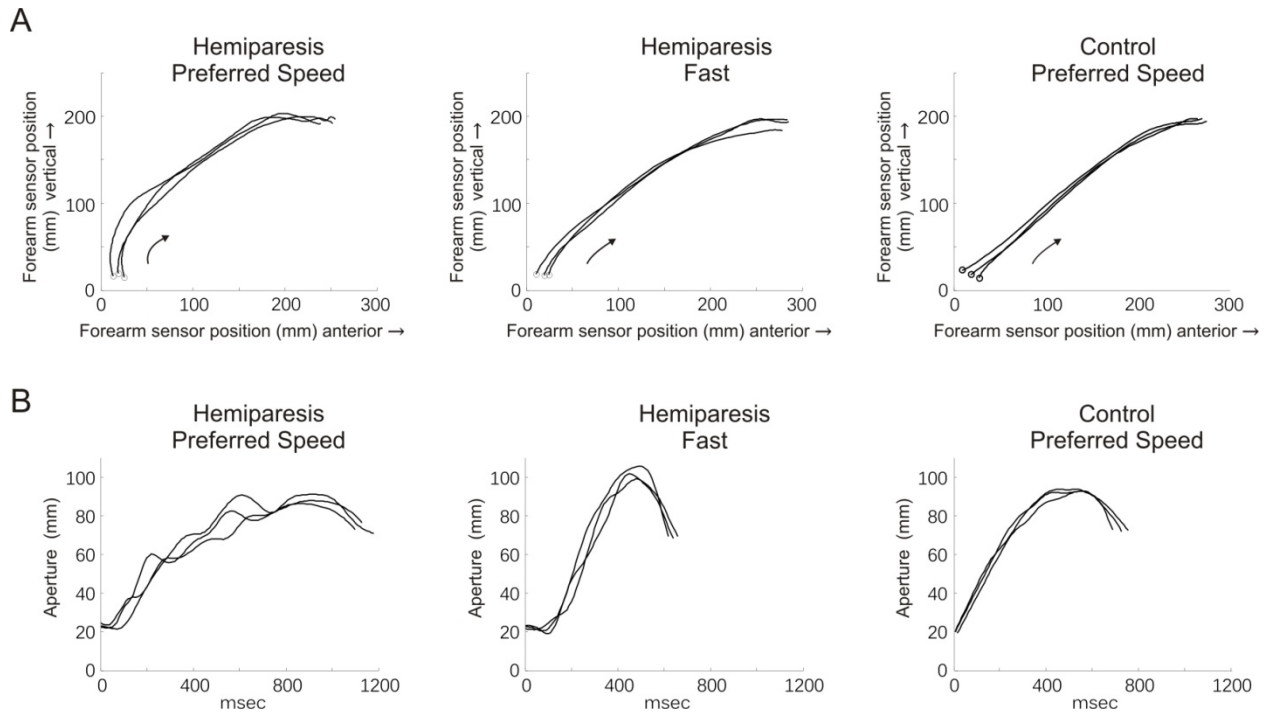
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1 Figure 3
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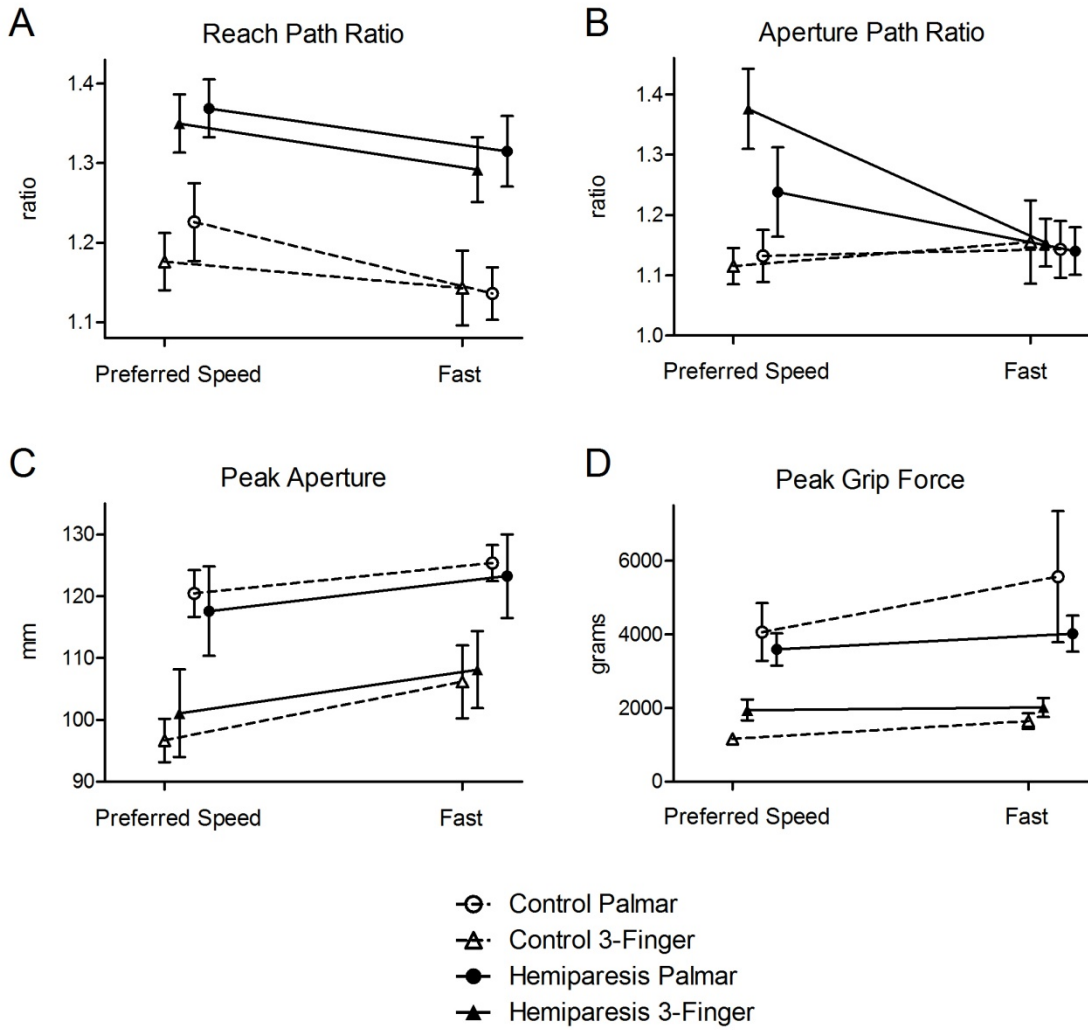
1 Figure 4
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