Effects of Robot Viscous Forces on Arm Movements in Chronic Stroke Survivors: A Randomized Crossover Study

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Research

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RESEARCH

Effects of Robot Viscous Forces on Arm Movements in Chronic Stroke Survivors: A Randomized Crossover Study

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Abstract

Background: Our previous work showed that speed is linked to the ability to recover in chronic stroke survivors. Patients moving faster on the first day of a three-week study had greater improvements on the Wolf Motor Function Test.

Methods: We examined the effects of three candidate speed-modifying fields in a crossover design: negative viscosity, positive viscosity, and a "breakthrough" force that vanishes after speed exceeds an individualized threshold.

Results: Negative viscosity resulted in a significant speed increase when it was on. No lasting after effects on movement speed were observed from any of these treatments, however, training with negative viscosity led to significant improvements in movement accuracy and smoothness.

Conclusions: Our results suggest that negative viscosity could be used as a treatment to augment the training process while still allowing patients to make their own volitional motions in practice.

Trial registration: This study was approved by the Institutional Review Boards at Northwestern University (STU00206579) and the University of Illinois at Chicago (2018-1251).

Keywords: stroke; reaching; speed; viscosity; crossover

Background

Stroke neurorehabilitation often uses the unique aspects of technology to improve motor recovery. While some researchers endeavored to simply assist movement to more closely resemble healthy patterns [1, 2, 3], others have attempted to exploit unique capabilities of robotics or graphic feedback to encourage neuroplasticity by augmenting error [4, 5, 6, 7, 8]. Even some traditional physical therapy exercises use mirrors to get the paretic side of the body to imitate the non-paretic side [9]. These are beneficial but far from a complete cure, and it remains to be seen what strategies emerge as optimal and what might still be left undiscovered.

An alternative strategy is to first uncover the attributes associated with better clinical movement outcomes, and then target training around these [10, 11]. Our previous work [12] employed a data-driven approach to model patient improvement using metrics derived from the movements themselves. We found that patient movement speed during the initial evaluation was most predictive of clinical changes. This speed was also the most strongly correlated with changes in the Wolf Motor Function Test (WMFT), making heightened speed a possible intervention for stroke.

However, before such an intervention might be tested in clinical trials, we need to establish effective methods for speeding up patients.

There are multiple possible training conditions that may achieve this increase, and here we compare three candidate classes of conditions. One approach to affect movement speed is to directly increase it with a negative viscous field; previous work [13, 14, 15, 16] showed that training with negative viscosity can improve patient movement and movement generalization abilities. Another possibility is to leverage the motor control mechanisms of error augmentation and after effects. Under this paradigm, patients would train with positive viscosity, under the expectation that their speed would increase as an aftereffect of that training when these resistive forces are removed [6, 17]. Finally, some research has shown that combining a resistive paradigm with a reward mechanism [18] may help patients learn better. In this case, patients will move in a positive viscosity field that attempts to slow them down, but moving above a certain speed is rewarded by a "breakthrough" where resistance vanishes. Subject may bias movements towards higher speeds to avoid the resistance.

In this preliminary clinical study, we simply compared the effects of these three paradigms on subject speed. Chronic stroke survivors participated in a single-visit crossover trial, where they trained for a short time under these three conditions. While we were mainly interested in the direct- and after-effects of these force paradigms on patient movement speed, we examined their effects on other movement metrics as well, such as error, efficiency, and smoothness.

Methods

Subject Population

We recruited 14 chronic hemiparetic stroke survivors (one patient was not able to participate after consenting due to a second stroke), 15-50 on the Upper Extremity Fugl-Meyer scale. Participants were excluded if they had multiple lesions or multiple stroke events, if they had bilateral paresis, or if they had Botox® treatments to the upper limbs within the last six months. Stroke survivors were recruited through the Clinical Neuroscience Research Registry of the Shirley Ryan AbilityLab and provided informed consent. This study was approved by the Institutional Review Boards at Northwestern University (STU00206579) and the University of Illinois at Chicago (2018-1251), and follows the guidelines of the Declaration of Helsinki. Figure 1 shows a CONSORT-style diagram (**CON**solidated **S**tandards **O**f **R**eporting **T**rials) for our crossover study, and Table 1 shows patient information at the time of participation in the study.

Experiment Design

Participants completed a single-visit crossover study. Subjects performed a targeted reaching task with their paretic arm attached to the Proficio® 3-DoF robot from Barrett Technologies (Figure 2). The Proficio allows three dimensional movement in a large workspace, approximating the normal range of human motion.

First, we evaluated baseline performance. Subjects reached for five minutes to targets distributed in a quarter-sphere under no robotic forces. Subjects then alternated between five minutes of reaching under each of the three experimental conditions, and five minutes of reaching with no forces to evaluate the aftereffects. We presented the three conditions to each participant in a pseudo-random order, to control for any possible ordering effect. A simplified 1-D representation of the three force types for our experimental conditions is shown in Figure 3 (A-C) and the timeline of the experiment is shown in Figure 3 (D).

Data Analysis

We resampled patient position data at 100Hz, then filtered it using a 7th order Butterworth filter with a 9Hz cutoff frequency. We extracted movement mean and maximum speed, and the various movement metrics that quantify accuracy (perpendicular error), efficiency (movement path distance), and smoothness (number of submovements)[12]. We focused our analysis for each condition on groups of five trials: prior to exposure to the robotic forces (pre-exposure), when the forces were initially experienced (early exposure), at the end of the five minute block experiencing the forces (late exposure), the reaction to the forces being turned off (aftereffects), and the end of the null field block before the next condition is experienced (retention). We modeled study outcomes using linear mixed effects regression of the fixed conditions (vs baseline), time, and random subject effects. We compared pairwise differences between conditions using post-hoc contrasts with Tukey's adjustment for multiple comparisons.

Results

Movement Speed

Negative viscosity produced significant speed increases during early exposure that persisted through late exposure ($p < 0.0004$, Figure 4). There was a significant difference between the effect of negative and positive viscosity forces ($p < 0.001$), and between negative viscosity and breakthrough forces ($p < 0.03$), but not between positive viscosity and breakthrough forces ($p > 0.48$). The order with which the force conditions were presented to the patients did not have a significant effect on speed ($p > 0.16$). The aftereffect of negative viscosity was a significant decrease in speed ($p < 0.02$) which did not persist at the end of washout (retention $p > 0.09$).

During early exposure, neither breakthrough nor positive viscosity had any significant effects on movement speed ($p > 0.11$). Both had a significant slowing effect on maximum speed ($p < 0.03$) but not on mean speed ($p > 0.055$) during late exposure. Neither had any significant effect on speed during washout ($p > 0.07$). There was no significant difference in the effects of positive viscosity and breakthrough forces during any stage of the experiment ($p > 0.48$) after correcting for multiple comparisons. The effects of negative and positive viscosity forces were significantly different ($p < 0.02$) for all but the retention stage ($p > 0.61$).

Other Movement Metrics

Movement error increased significantly during early exposure to negative viscosity ($p = 0.004$, Figure 5A). The effect was no longer significant by late exposure ($p = 0.064$). However, both the aftereffect and retention had a significant reduction in movement error ($p < 0.023$). Training with positive viscosity forces yielded a significant increase in movement error during exposure ($p < 0.01$) but no significant aftereffects. Breakthrough forces had no significant effect on error during exposure, but showed a significant error reduction as an aftereffect ($p < 0.02$). Interestingly, the retention movement error was affected by the order the force types were presented to patients ($p = 0.04$), other stages were not affected by the order ($p > 0.06$).

Movement distance showed behavior similar to movement error (Figure 5B), where negative viscosity resulted in worse performance during exposure ($p < 0.0001$) but significantly improved performance as an after effect ($p \leq 0.001$). Positive viscosity had no significant effects during any stage, while breakthrough showed a significant improvement only during the aftereffect ($p \leq 0.001$).

Movement smoothness, as quantified by the number of speed peaks, was significantly worse during exposure ($p \leq 0.0099$) and significantly better during washout ($p \leq 0.033$, Figure 5C). Interestingly, all force types showed a significant improvement in movement smoothness in early aftereffects ($p \leq 0.031$), though only after training with negative viscosity did patients retain that improvement.

Finally, there was a significant increase in pre-movement speed during exposure to negative viscosity (Figure 5D). There was no significant effect for any of the three force types on this pre-movement tremor by late washout, though training with negative viscosity showed an average reduction in pre-movement speed.

Discussion

We looked for evidence of speeding patients up in both the direct effects when we turn on robotic forces and after effects after minutes of exposure then turning the forces off. As we expected, negative viscosity produced the largest direct effect (an increase in speed), since it was directly pushing patients to move faster. Speeds decreased by the end of exposure as they adapted, although they remained faster than baseline – a prolonged direct effect. Interestingly, we observed no speed-related after effects from any of our force treatments and any mismatch from baseline behaviour quickly dissipated.

During exposure to positive viscosity, patients exhibited the slower movements we expected, though this slowdown was not statistically significant in most cases. There was a minor increase in movement speed as an aftereffect, which was also not significant. Ultimately, patients behaved as we expected during and after experiencing positive viscosity, but the effects were very small compared to their baseline movements.

We expected that breakthrough forces would bias towards faster movements during late exposure and the early aftereffect due to this condition rewarding faster movements. We instead saw a reduction in movement speed. This can be due to incomplete learning of the forces, where patients did not have enough experience with the breakthrough condition to sufficiently bias their movements. Another explanation can be that breakthrough forces do not have the desired effect on patient movement speed. Either way, in a direct comparison with negative and positive viscosity under similar force magnitudes and length of exposure, breakthrough forces did not succeed in increasing patient speed.

Negative viscosity reduces patients' ability to control their arm movements during the initial ballistic phase. This led to a significant reduction in movement accuracy, effectiveness, and smoothness, as patients tried to counteract the destabilising force.

These effects were reversed, as expected, once the forces were turned off, and patients significantly improved their reaches.

There were smaller, mostly non-significant effects of the other force conditions on these movement metrics. Overall, patients did not improve their reaches after training with positive viscosity or breakthrough forces.

We expected incomplete learning and/or incomplete washout due to our short exposure and null field blocks. Hence, we presented the forces to our participants in a randomized order and tested for any ordering effect. Out of 30 linear mixed effects models, the order the forces were experienced was significant in only two cases: late exposure movement distance, and retention movement error. This could be due to a few outliers in our small sample of patients, since in both cases the p-values were just below the significance level ($p \approx 0.04$).

It is important to note that this study was not powered. Our goal was to perform a crossover exploration into the effects of different types of robotic forces, while at the same time accounting for the possibility of ordering effects. Since there were $3! = 6$ possible order sequences for the three force types, we wanted to examine data from at least two patients per order sequence (1) to reduce the effects of possible outliers, which increased our number of participants to 12. We did not examine the data before all participants had completed the study. Due to the first patient having some initial difficulty moving the robot arm, we enrolled one additional patient in case parts of the movement data from the first patient was unusable. We were ultimately able to utilize the data we collected from all patients, and had a grand total of 13 participants.

This study showed that negative viscosity had a strong direct effect at increasing patient speed, and that its usefulness as a treatment for chronic stroke survivors was bolstered by an improvement in movement accuracy, efficiency, and smoothness after the training. We are currently piloting training with negative viscosity over multiple sessions to improve clinical outcomes in chronic stroke survivors, as a prelude to a full clinical trial.

Conclusions

In a direct comparison between the three force conditions that may increase movement speed, patients significantly increased their speed only as a direct effect of negative viscosity. Positive viscosity and breakthrough forces had no effect on patient speed. After the forces were removed, only negative viscosity showed significant improvements in other movement metrics measuring accuracy, efficiency, and smoothness. We conclude that training to increase movement speed should be conducted using negative viscosity. Even though we did not achieve the desired lasting effect on movement speed, the improvements in other movement parameters shows promise for negative viscosity as a potential treatment.

List of abbreviations

- UEFM: Upper Extremity Fugl-Meyer
- WMFT: Wolf Motor Function Test

Declarations

Ethics approval and consent to participate

This study was approved by the Institutional Review Boards at the University of Illinois at Chicago (2018-1251) and Northwestern University (STU00206579). All members of the research team were approved for conducting research with human participants.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Author's contributions

YAM collected, analyzed, and interpreted the data, and wrote the initial manuscript. SA worked on and provided direction for the statistical analysis. JLP directed the research and study design. All authors edited and reviewed the manuscript.

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Figures

Figure 1 CONSORT-style diagram for speed crossover. One patient dropped from the study after having a second stroke, which was disqualifying. Data was collected and analyzed for 13 total patients.

Figure 2 Experiment Setup. Patients reached unimanually, alternating between a central home position and randomly to one of eight different target locations. The study was conducted using the Looking Glass virtual reality system and the Barrett Proficio robot arm.

Figure 3 Experiment Conditions and Timeline (A) Timeline of the experiment, each "block" of trials lasted for five minutes, and there was a short break (30-60 seconds) in after each block. **(B)** Negative viscosity. Forces were proportional to velocity in all three directions, we drove the forces to zero at higher speeds for safety. **(C)** Positive viscosity. Similar to negative viscosity but the forces acted opposite to the direction of motion, slowing the participants. **(D)** Breakthrough. Forces were proportional to velocity until the participants reached 75% of their baseline speed, forces were then removed as a reward for reaching faster speeds.

Figure 4 Effect of experiment conditions on altering patient speed. Error bars represent 95% confidence interval. Negative viscosity had the strongest effect on participant speed, though the aftereffect was opposite to what we hoped to achieve (on average, participants slowed down, though not significantly). There was no significant difference between the effects of positive viscosity and breakthrough, and no significant change from baseline.

Figure 5 Effect of experiment conditions on various movement features. (A) Movement error measured using maximum perpendicular distance. (B) Movement length measured as the magnitude of the distance covered by the subject's arm. (C) Movement smoothness measured as the number of peaks in the speed profile. (D) Pre-movement speed measued as the average speed after target is displayed and before subjects begin moving.

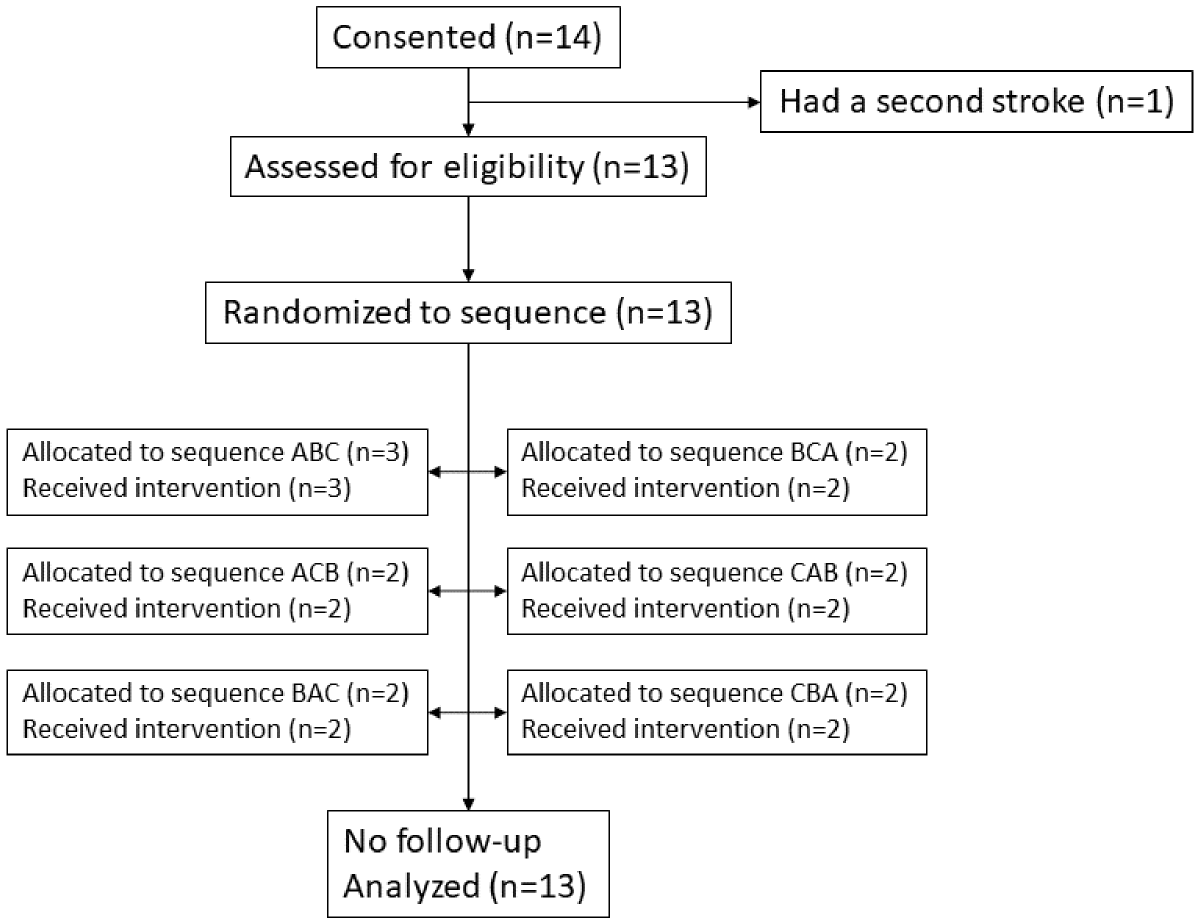
Tables

Table 1 Patient information for this study ($N = 14$)

Subject ID	Age (yrs)	Time Since Stroke (months)	Sex	Dominant Side	Affected Side	UEFM Score
SP01	59	29	M	right	right	26
SP02	52	70	M	right	left	44
SP03[a]	64		M			39
SP04	59	45	M	left	right	37
SP05	37	52	M	right	right	32
SP06	64	95	M	right	left	35
SP07	83	32	M	right	right	46
SP08	45	75	F	right	left	23
SP09	67	11	M	right	left	37
SP10	50	157	F	right	left	33
SP11	58	50	F	right	right	40
SP12	57	29	F	right	left	24
SP13	67	49	M	right	right	23
SP14	46	43	F	right	left	34

[a] SP03 consented but did not perform the study due to a second stroke

Figures



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CONSORT-style diagram for speed crossover. One patient dropped from the study after having a second stroke, which was disqualifying. Data was collected and analyzed for 13 total patients.

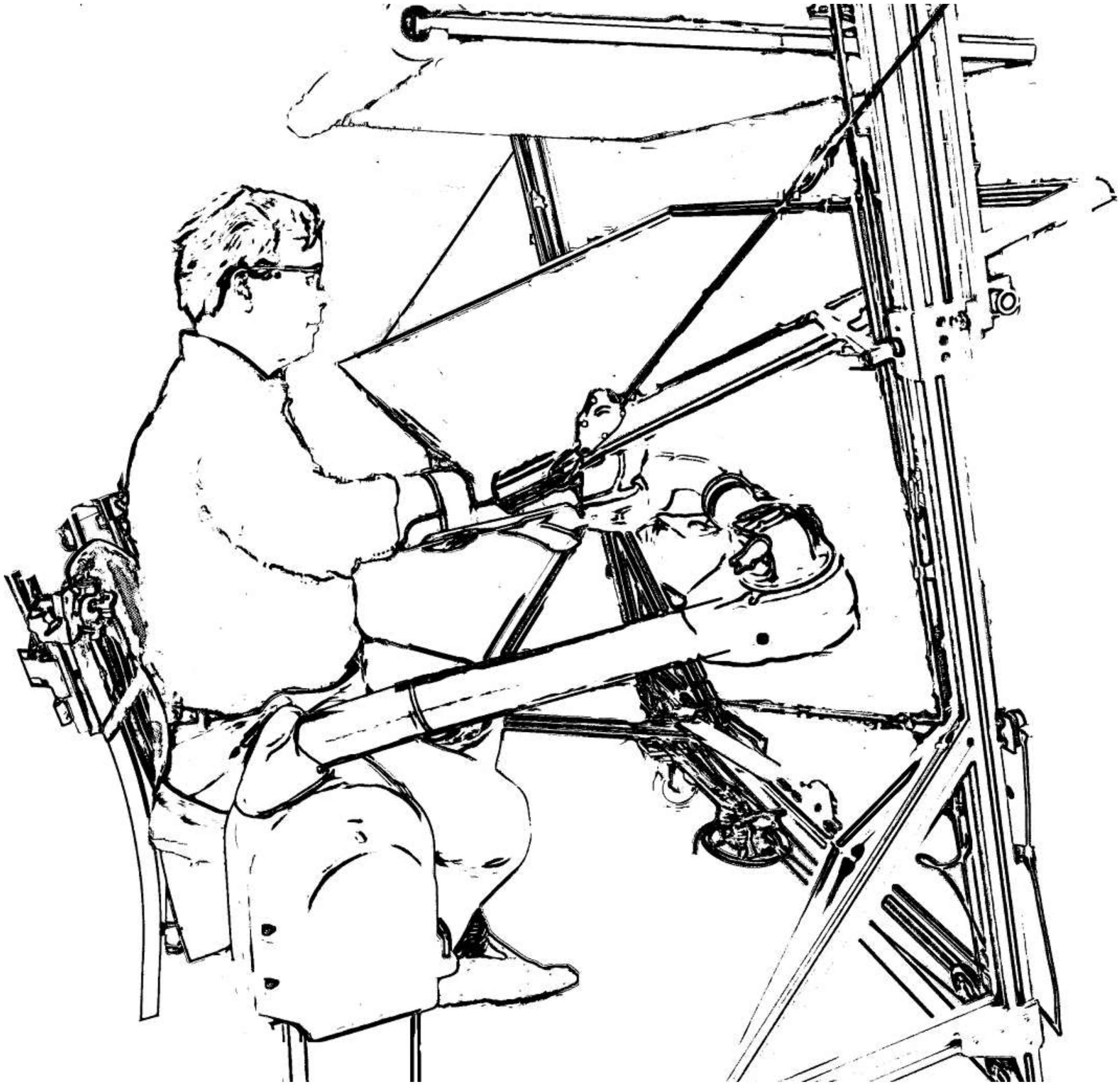
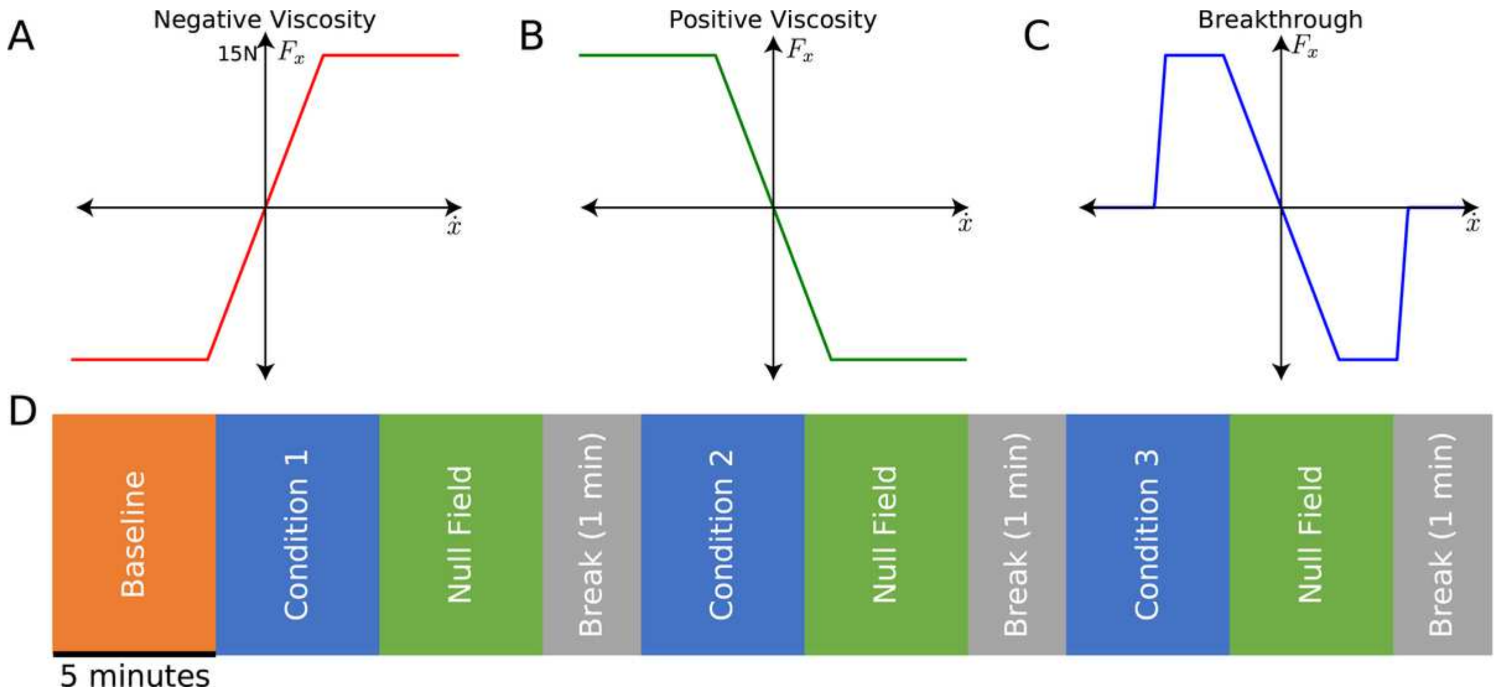


Figure 2

Experiment Setup. Patients reached unimanually, alternating between a central home position and randomly to one of eight different target locations. The study was conducted using the Looking Glass virtual reality system and the Barrett Procio robot arm.



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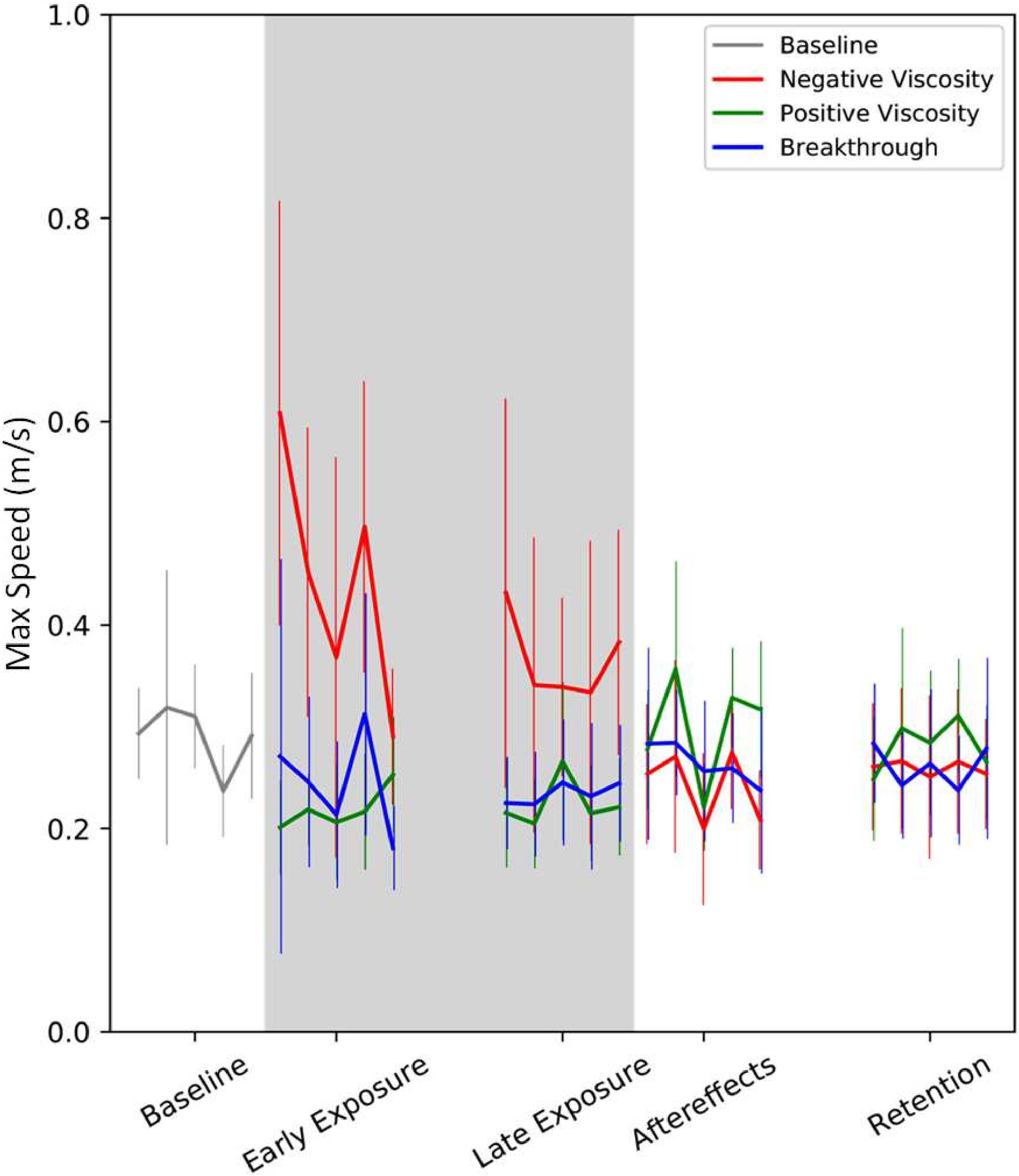

Figure 4

Effect of experiment conditions on altering patient speed. Error bars represent 95% condence interval. Negative viscosity had the strongest effect on participant speed, though the aftereffect was opposite to what we hoped to achieve (on average, participants slowed down, though not signicantly). There was no signicant difference between the effects of positive viscosity and breakthrough, and no signicant change from baseline.

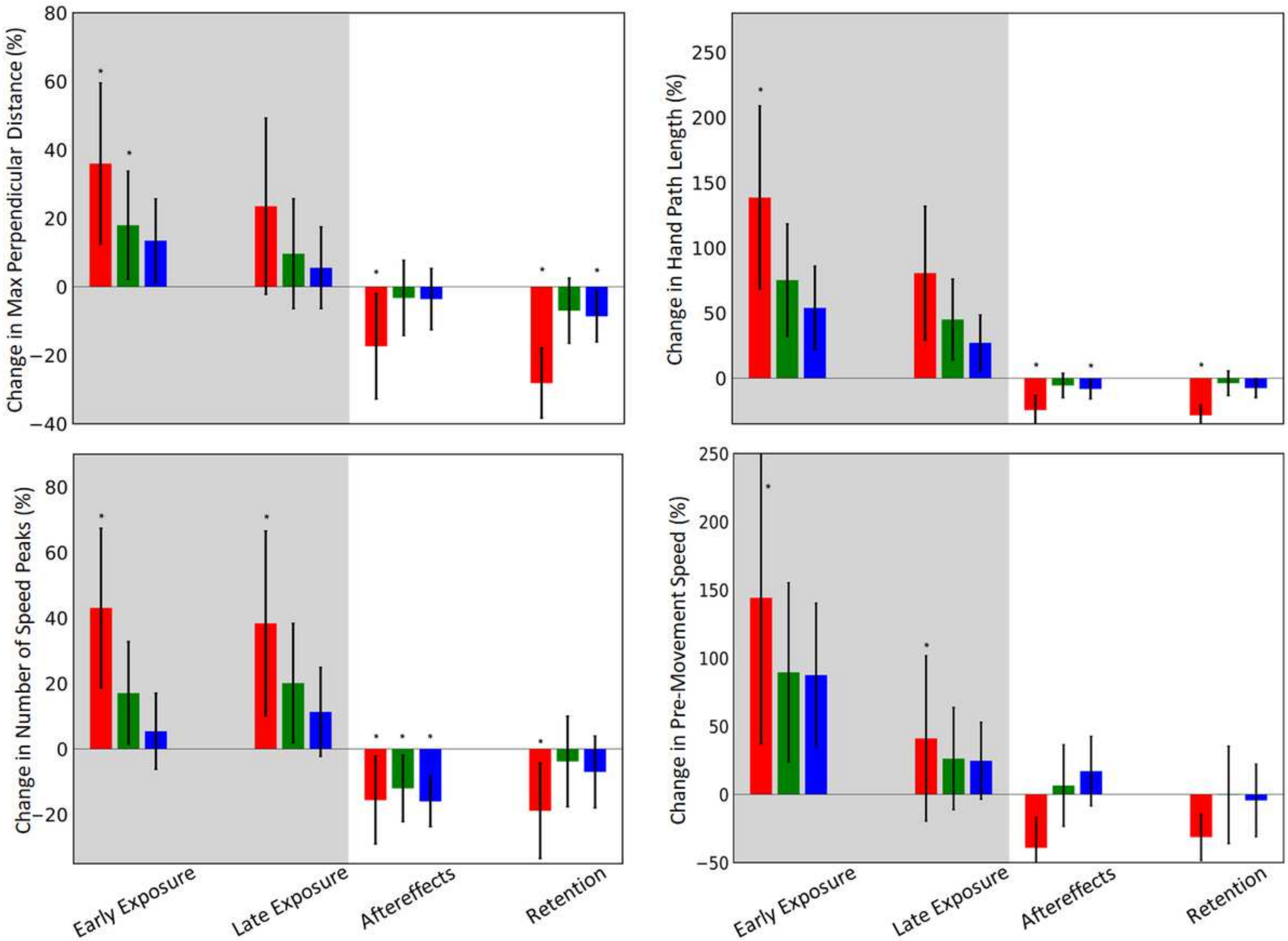

Figure 5

Effect of experiment conditions on various movement features. (A) Movement error measured using maximum perpendicular distance. (B) Movement length measured as the magnitude of the distance covered by the subject's arm. (C) Movement smoothness measured as the number of peaks in the speed prole. (D) Pre-movement speed measued as the average speed after target is displayed and before subjects begin moving.