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Variations in neuromuscular electrical stimulation's ability to increase reach and hand opening during voluntary effort after stroke

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Abstract

Functional Electrical Stimulation (FES) has shown potential as a mechanism to augment functional arm and hand movement after stroke. However, neuroprostheses that combine voluntary effort and FES must account for co-activation patterns (synergies) that limit movement. The goal of this study is to explore the conditions under which voluntary effort and FES can be combined to achieve useful reach and hand opening in different subjects. Subjects performed a reach and hand opening task where different levels of voluntary effort and FES were applied to produce reach and hand opening while measuring the resulting hand opening and distance from a target. Initial results indicate that there are significant variations between participants and how much effort can be exerted while still eliciting effective reach and hand opening.

I. Introduction

Stroke is a leading cause of disability in the US. Six months after their stroke, 50% of ischemic stroke survivors over the age of 64 still have a degree of upper limb hemiparesis [1]. This hemiparesis limits arm and hand function, making bimanual tasks difficult if not impossible. It can be expressed as co-activation patterns across multiple joints (i.e. synergy patterns) [2]. Typically, effort to abduct the arm is accompanied by involuntary flexor contractions that oppose reaching movements and close the hand. These synergy patterns have been well quantified [3] and appear to be expressed in proportion to effort [4–6].

Functional Electrical Stimulation (FES) of paretic muscles has the potential to elicit functional limb movements, such as reaching and hand opening [7]. For example, electrical stimulation of finger and elbow extensors [8–11] can produce reach and hand opening while the participant is relaxed. However, when the user exerts effort to abduct and reach with their arm, the hand and elbow do not extend as much in response to stimulation as when the person remains relaxed [12], presumably because their effort to reach produces involuntary flexor contractions [8, 13, 14]. Therefore in order to receive maximum movement from the stimulation, the user must remain relaxed, which is counterintuitive.

The goal of this study is to evaluate how much reducing voluntary effort for reach and hand opening and augmenting it with FES increases reach and hand opening for different participants. There are two hypotheses for this study: 1) Reducing effort for voluntary reach and hand opening, while augmenting partial effort with stimulation will increase hand opening at the same position, and 2) Stimulation to augment reach and hand opening produces greater reach with an equal or greater level of hand opening than voluntary reaching effort alone produces. If these hypotheses are true, limiting the effort used as the command signal for an FES system may allow stimulation to produce effective hand opening.

II. Methods

A. Participants

Participants were recruited from an outpatient stroke clinic. The primary inclusion criteria included: 1) being at least 6 months post-stroke, 2) the ability to follow 3-stage commands, 3) the ability to reach forward at least 10 cm while the elbow and wrist were supported by the investigator, 4) the inability to fully reach and open the hand while the arm is unsupported, and 5) an upper extremity Fugl-Meyer score between 10 and 50. Exclusion criteria include 1) uncompensated hemineglect, 2) apraxia, or 3) severe shoulder or hand pain. Participants provided informed consent in accordance with the Declaration of Helsinki prior to participation in this study, which was approved by an Institutional Review Board. Three participants have completed this study to date. Their details are in Table 1.

B. Setup

Participants performed a series of reach and open the hand tasks (described below) while seated with the trunk restrained. Arm position was measured by an optical tracking system (Optotrak) and a custom device measured the aperture of hand opening [15]. Partial forearm support was provided by a mobile arm support (Jaeco) in all of the trials. A participant is shown performing one of the tasks in Figure 1.

C. Experimental Procedures

Before any reaching task sessions, a Fugl-Meyer Motor Assessment and modified Ashworth test were carried out by an occupational therapist to characterize the degree of upper limb motor impairment. Participants returned to the lab for up to four more sessions to learn the reaching tasks and become accustomed to the sensation of electrical stimulation. During the two final sessions, hand opening and arm kinematic data were collected for analysis.

Participants were instructed to reach to a target and attempt to open the hand as much as possible. This task was repeated using a combination of different reach and hand opening conditions that incorporated different levels of stimulation and voluntary effort. One set of shoulder and elbow muscles was stimulated to increase reach. A second set of muscles was stimulated to produce hand opening.

There were three reaching conditions and three hand opening conditions for a total of nine combinations. The three different reaching conditions were: 1) voluntary effort alone (Vol.),

2) stimulation (Stim) of the triceps and anterior/middle deltoids while the participant remained relaxed, and 3) partial voluntary reach and the same stimulation parameters as condition 2 (V&S). The participant was asked to estimate effort and try to limit reaching effort to half of their maximum. The level of partial effort was not well constrained or quantified for these movements. The three different hand opening conditions were: 1) voluntary effort alone (Vol.), 2) stimulation (Stim) of hand opening muscles while the participant remained relaxed, and 3) maximum voluntary effort to open the hand and the same stimulation parameters as condition 2 (V&S). All of the combinations are shown in Table 2.

During the first practice session, electrode positions and stimulation levels were found that produced reach and hand opening without eliciting pain while the participant was relaxed. The anterior and middle deltoids were targeted for shoulder abduction and flexion, and the triceps was targeted for elbow extension. The hand muscles targeted varied between participants as different participants were able to achieve stimulated hand opening with fewer muscles. The targeted muscles included extensor digitorum communis, extensor pollicis longus, and abductor pollicis brevis. While surface stimulation could produce hand opening and elbow extension without producing pain, it is difficult to elicit full shoulder abduction and flexion with surface stimulation. There are additional muscles beyond the deltoids that contribute to shoulder abduction and flexion at both the glenohumeral joint and the scapula. These muscles are deeper and difficult to recruit with surface stimulation due to nerve depth and poor muscle selectivity. For the same reasons, it can be difficult to fully stimulate the axillary nerve without causing pain or activating nearby muscles. Due to the limits of surface stimulation in producing shoulder flexion and abduction, a mobile arm support also provided an upward force at the forearm, reducing the force that FES needed to generate at the shoulder. The amount of support was consistent across trials for each participant. The vertical support ranged from 22–26 N.

A target was placed in front of the participants. The participants were cued to reach to the target and open their affected hand under different combinations of voluntary effort and electrical stimulation at the arm and hand. Once the arm reached a steady position, the participant was instructed to maintain their reaching effort while attempting one of the combinations of hand opening. We provided the hand opening cue for four seconds. These tasks were repeated using two different target positions. The first target position is half of the distance from the participant's relaxed position to the furthest distance that the participant could reach. The second target was at the furthest position the subject could reach with stimulation, which was beyond the distance of voluntary reach for some participants.

D. Data Analysis

For each position, the average hand opening and the distance between the target and center of the wrist were calculated over the last second of each trial. When all of a participant's trials of a certain combination of reaching and hand opening conditions had hand opening increase less than a centimeter, the result was treated as no hand opening. This was done to prevent passive hand opening from appearing like active hand opening. ANOVA's were used to compare the amount of hand opening and reach achieved using the different reaching conditions (voluntary effort alone, stimulation and partial voluntary effort, stimulation alone) hand opening conditions (voluntary effort alone, stimulation alone, and combined maximum voluntary effort and stimulation), positions (near and far), and subjects as factors. Subjects were a random factor while the rest were fixed factors. If the factors were statistically significant, the Tukey-Kramer comparison of means was used to determine which factors were statistically different.

III. Results

When voluntary effort (Vol.) was reduced and replaced with FES (Stim), hand opening and reach generally increased. There were significant interactions between the multiple factors affecting the amount of hand opening: subjects and hand opening conditions ($p<0.001$), subjects and reaching conditions ($p<0.001$), subjects and target position ($p<0.001$), and reach condition and hand opening condition ($p<0.001$). There were also interactions affecting the distance from the target: subject and reaching condition ($p<0.001$), target position and reaching condition ($p<0.001$), and the subject and hand opening condition ($p=0.007$). Since the subjects interact with so many of the other factors, the hypotheses need to be examined on a subject by subject basis.

Example data showing reach and hand opening are shown in Figures 2, 3, and 4 for each subject. The passive closing limit in the figures is due to the hand sensor. Post-hoc t-tests were done using subjects as a fixed factor to evaluate the hypotheses on a subject by subject basis. For S1, stimulation significantly increased reach and hand opening, but voluntary effort limited or removed any gain ($p<0.05$). For S2, stimulation was needed to produce effective hand opening. While there was statistical significance ($p<0.05$) when voluntary reaching effort was exerted during hand stimulation alone, the difference of a centimeter in hand opening is relatively small from a clinical perspective. For S3, stimulation increased hand opening ($p<0.05$), but the best hand opening resulted when voluntary reaching effort was limited and augmented with stimulation.

In addition to affecting hand opening, stimulation for reach decreased the subject's reaching error. S1 was able to reach closer to both the near and far targets when stimulation for reach was applied ($p<0.05$). S2's reaching distance was smaller on average during stimulated reach, but not statistically significant. S3 was able to reach to both the near and far target without stimulation, so reaching stimulation did not improve reach.

IV. Discussion

Stimulation is capable of producing effective hand opening and reach similar to how FES has been used to increase torque in the presence of voluntary effort [16]. As seen in Figures 2, 3, and 4, there are significant differences between the responses in different participants. These three participants suggest three very different approaches to increase function with FES.

FES produced effective hand opening in S1 when he was not exerting effort to reach or open his hand, but produced minimal amounts of hand opening when full effort for reach or hand opening was exerted. In this individual it would be crucial to limit effort to as little as required to derive a command signal for an assistive FES system. Similarly, this participant had difficulty reaching. While he was able to reach the near target with the partial mechanical support, he was unable to reach to the far target without FES assistance.

In contrast, S2 would benefit from a different approach. He had no volitional hand opening (visible twitch only) and limited reaching ability, and did not exhibit significant co-contraction and co-activation patterns. While there may be difficulties generating sufficient effort to elicit an effective command signal, there would be no reason to limit the volitional effort exerted.

S3 has some ability to open his hand when he is not actively reaching. With the partial support provided to enable effective force assistance from the stimulation, he was able to volitionally reach to the far target. Additionally he can partially open his hand when not actively reaching. During volitional reach though he is unable to volitionally open his hand.

This indicates that despite his ability to produce volitional reach, there is value in providing assistance for reach in order to elicit hand opening.

These data support Hypothesis 1 (hand opening) and Hypothesis 2 (FES for reach and hand opening). It should be noted that while S3's hand opening was improved during reach, he already had full reach with the mechanical support.

In S1 and S3, reducing voluntary effort likely limits the expression of synergy patterns, which would have overpowered the effect of hand opening electrical stimulation. Proximal upper extremity stimulation was not shown to affect voluntary finger flexion torque [17] and triceps stimulation did not increase the stretch reflex of finger flexors [18]. This reduction in effort may have limited the synergy patterns, thereby allowing stimulation to have a greater effect at both the arm and hand. It is also important to note that while partial effort combined with FES did not produce as much hand opening as FES alone, the partial reaching effort did not completely overpower the effect of FES at the hand.

Future experiments should include percutaneous stimulation, isometric force measurements, and electromyogram (EMG) analysis. Percutaneous stimulation can target deeper muscles and allow more selective stimulation. Measuring isometric forces at multiple joints enables modeling the multijoint interactions similar to [6, 19] and assessing thresholds of acceptable effort. Recording EMG provides information about co-contraction levels across joints, level of muscle activation, and timing of the muscle patterns.

While reducing effort is one method to limit coactivation and allow stimulation to have a greater effect, other therapies are being developed to disconnect the synergy patterns. Ellis et al. [20] have developed a therapy that unlinks the synergies between the shoulder and elbow, increasing reach for the same level of shoulder abduction. The effect on the hand was not measured in these experiments. Similarly, afferent inputs (vibration) have been shown to reduce EMG levels across a joint during reaching movements [21]. Therefore a combination of therapeutic and neuroprosthetic interventions would be useful.

These variations between participants indicate a need for assistive devices to be tailored to specific individuals. Design of an effective device requires an understanding of their co-activation and co-contraction patterns. Similarly, this requires knowing if that level of effort and residual motor control provides an effective command signal.

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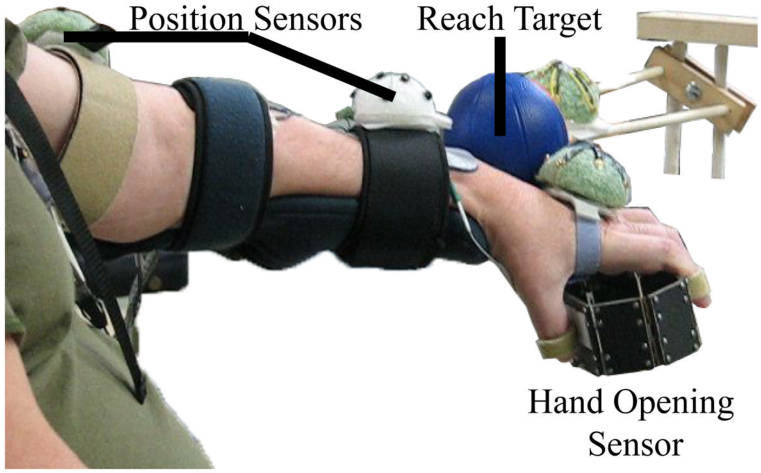

Fig 1.
Example of a participant performing the reach and open task.

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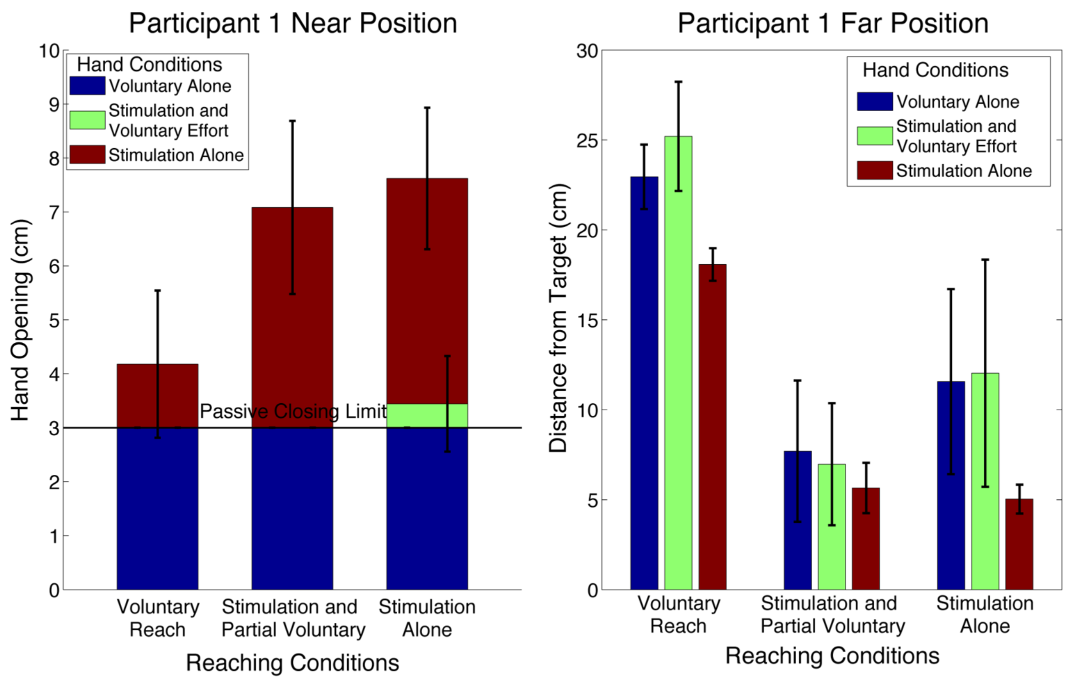

Fig 2.
S1 data for hand opening (near position) and distance (far position)

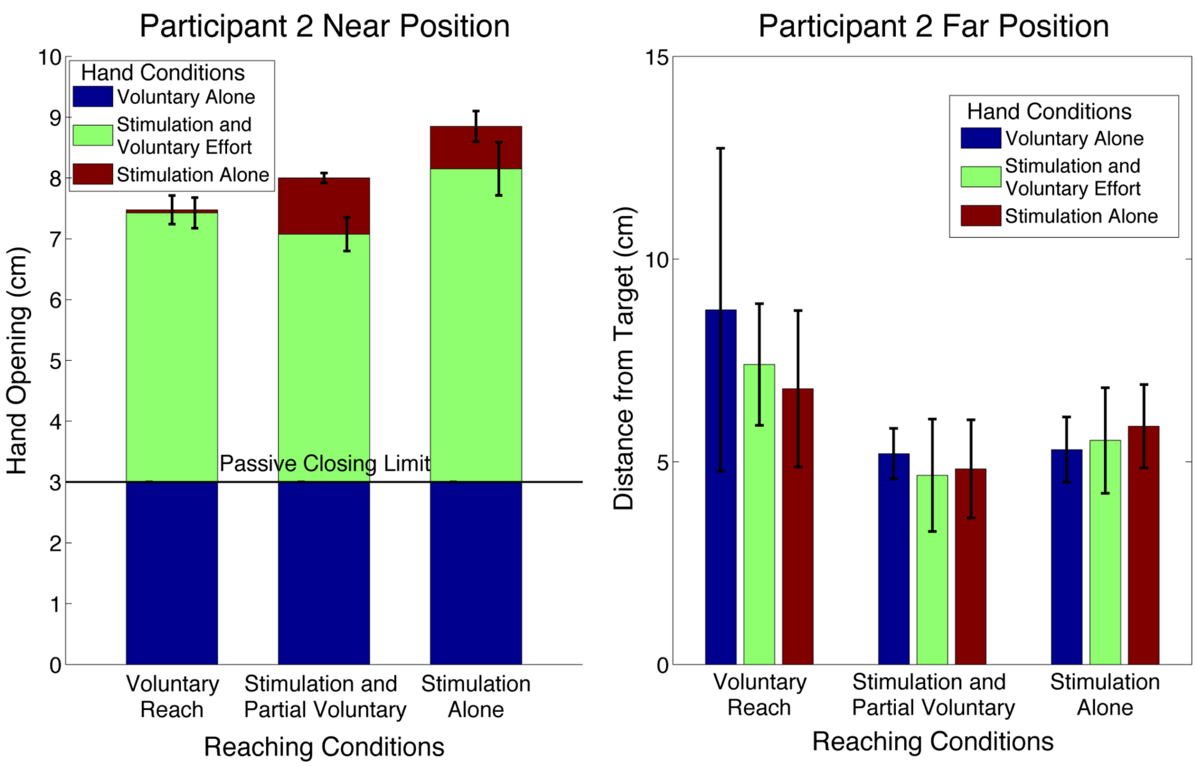

Fig 3.
S2 data for hand opening (near position) and distance (far position)

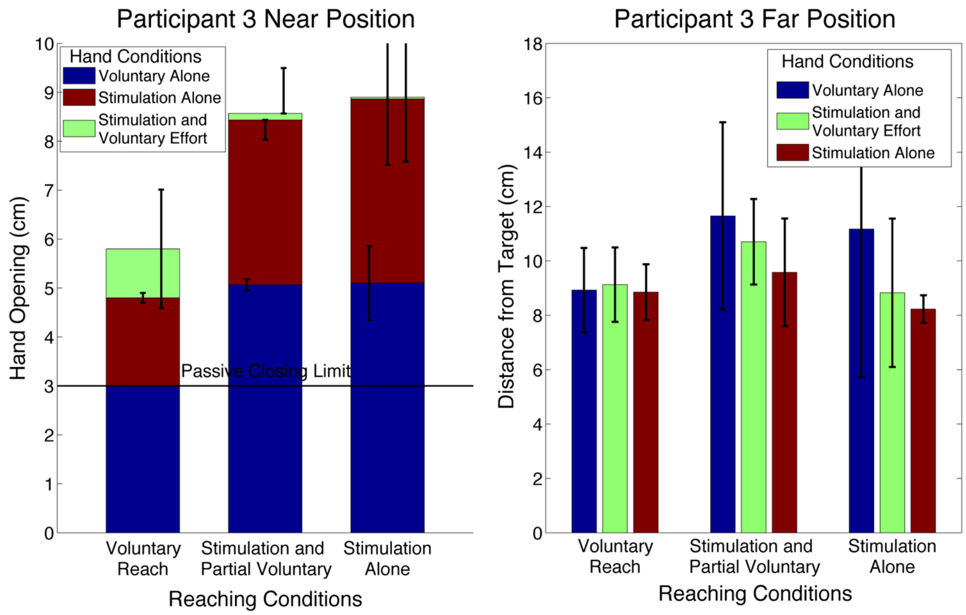

Fig 4.
S3 data for hand opening (near position) and distance (far position)

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Table 1

Participant Demographics.

	Age	Dominant/Affected Side	Time Since Stroke	FMA (arm)	mASH (elbow flexors)	mAsh (finger extensors)
S1	60	R/L	9 yrs	13 (11)	1+	1
S2	55	R/R	5 yrs	19 (17)	3	2
S3	58	R/R	3 yrs	29 (19)	3	*

Abbreviations – FMA: upper limb portion of Fugl-Meyer Motor Assessment, 66 point maximum, shoulder/elbow/forearm component in parentheses, 34 point maximum; mASH: modified Ashworth spasticity test; Side: R-Right, L-Left.

* Data not recorded.

Table 2

Combinations of reach and hand opening – Voluntary effort alone: Vol; Stimulation alone: Stim; Stimulation and voluntary effort: V&S

		Reach Conditions		
		Voluntary (Vol. Reach)	**Vol. and Stim (V&S Reach)**	**Stimulation (Stim Reach)**
Hand Conditions	Voluntary (Vol. Hand)	Vol. Reach Vol. Hand	V&S Reach Vol. Hand	Stim Reach Vol. Hand
	Vol. and Stim (V&S Hand)	Vol. Reach V&S Hand	V&S Reach V&S Hand	Stim Reach V&S Hand
	Stimulation (Stim Hand)	Vol. Reach Stim Hand	V&S Reach Stim Hand	Stim Reach Stim Hand