International Journal of
Physical Medicine & Rehabilitation

Klink et al., Int J Phys Med Rehabil 2013, 1:8
DOI: 10.4172/2329-9096.1000169

Research Article Open Access

Effects of Functional Electrical Stimulation with and without a Wrist-Hand Orthosis on Hand Opening in Individuals with Chronic Hemiparetic Stroke: A Pilot Study

Nicole van Klink[1,2], Julius Dewald[1-4], Jane Sullivan[1] and Jun Yao[1]*

[1]*Department of Physical Therapy and Human Movement Science, Northwestern University, USA*
[2]*Department of Biomedical Engineering, University of Twente, The Netherlands*
[3]*Department of Biomedical Engineering, Northwestern University, USA*
[4]*Department of Physical Medicine and Rehabilitation, Northwestern University, USA*

Abstract

Objective: Many individuals with stroke cannot open their affected hand in a functional way: they either produce insufficient hand opening, or achieve hand opening while flexing their wrist. Insufficient hand-opening in post-stroke individuals can be improved by applying functional electrical stimulation (FES) to finger/thumb extensors. However, how to reduce the coupling between finger extension and wrist flexion is still unknown. Both FES to wrist extensors and a wrist-hand orthosis (WHO) can assist holding the wrist in a close-to-neutral position. This may or may not improve purposeful use of the paretic arm, depending on how it will interfere with hand opening. Therefore, this study investigated how using either FES or WHO to maintain the wrist in a close-to-neutral position will impact the FES-assisted hand opening.

Methods: We recruited twelve individuals with moderate to severe stroke to participate. They performed maximal hand opening with or without assistance from FES/WHO. Hand opening distance and wrist flexion angle were measured.

Results: Our results demonstrated that FES applied to the finger extensors resulted in a trend of larger opening distance ($p<0.1$), but was associated with a significant reduction in wrist extension angle. Additional FES to wrist extensor didn't create any significant effect as compared to FES to finger/thumb extensors. Using a WHO significantly reduced wrist flexion angle ($p<0.01$), and has a trend in reducing the finger opening distance ($p<0.1$) although only by a 2 mm distance. When comparing the effect of 'FES to finger extensors with WHO' and 'FES to wrist and fingers extensors without WHO,' we found no difference in hand opening distance ($p>0.2$); however, a trend of reduced wrist flexion angle ($p=0.057$) when using WHO combined with FES.

Conclusion: These results suggest that combined FES and WHO should be considered when designing interventions or devices to enhance hand opening in individuals with stroke.

Keywords: Upper limb neuroprosthesis; Stroke; Functional electrical stimulation; Wrist-hand orthosis; Hand opening; Wrist extension

Introduction

Upper Extremity (UE) motor impairment is a severe effect of stroke. Only 12% to 18% of individuals with stroke will regain full UE function [1]. Six months after the stroke, 33% to 60% still have a degree of UE hemiparesis [1,2]. Motor impairments strongly affect daily life activities [3,4]. For individuals with severely affected arms post stroke, the evidence that conventional therapy can restore meaningful hand function is not strong [4-8].

Many individuals with moderate to severe stroke either produce insufficient hand opening, or achieve hand opening while flexing their wrist. In order to improve hand opening, functional electrical stimulation (FES) to finger extensors has been used, which also decreases spasticity, and improves muscle strength and range of motion following stroke [1,9,10]. However, how to achieve a reduced wrist flexion while hand opening is still unknown. In healthy individuals, hand-opening during functional activities is typically accomplished with a neutral or slightly extended wrist position. Such combination becomes difficult to achieve for many individuals with moderate to severe stroke, may be due to the increased stiffness and shortening in the long finger flexor muscles/tendons. Instead, an abnormal coupling between finger extension and wrist flexion occurs and ultimately interferes with an effective use of the paretic hand.

To assist holding the wrist in a neutral position, both 'FES to wrist extensor' and 'a wrist-hand orthosis (WHO)' can be used. This additional assistance for wrist extension may or may not improve purposeful use of the paretic arm, depending on how such device will interfere with the hand opening ability. Previous reports showed the combined use of a WHO with wrist/finger extension FES enhanced hand function [11,12]. However, post-stroke stiffness or shortening in the long finger flexor muscles/tendons may result in finger flexion during wrist extension. This could interfere with hand opening or the release of objects. In short, the effect of using FES or WHO to maintain a neutral wrist position on FES-assisted hand opening has not been investigated yet. To answer this question, we compared the maximum hand opening distance and wrist flexion angle produced by voluntary effort and assisted by using FES on several different muscle groups with or without a WHO.

***Corresponding author:** Jun Yao, Assistant Professor, Department of Physical Therapy and Human Movement Sciences, Northwestern University, 645 N. Michigan Ave, Suite 1100, Chicago, IL 60611, USA, Tel: (312) 908-9060; Fax: (312) 908-0741; E-mail: j-yao4@northwestern.edu

Received September 20, 2013; **Accepted** November 28, 2013; **Published** November 30, 2013

Citation: Klink Nvan, Dewald J, Sullivan J, Yao J (2013)Effects of Functional Electrical Stimulation with and without a Wrist-Hand Orthosis on Hand Opening in Individuals with Chronic Hemiparetic Stroke: A Pilot Study. Int J Phys Med Rehabil 1: 169. doi:10.4172/2329-9096.1000169

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Materials and Methods

Subjects

Fifteen subjects with moderate to severe arm motor impairment following chronic stroke (> 1 year post-stroke) were recruited from a university-based stroke registry. The level of motor impairment of each subject was determined by the Fugl-Meyer motor assessment (FMA) [13]. Subjects with moderate to severe motor impairment (FMA<40) were included. Subjects were excluded if they had a cardiac pacemaker, other neurologic deficits, or preexisting functional limitations of the affected arm. Among the 15 recruited subjects, 3 had to be excluded due to incomplete or unreliable data. Characteristics of the 12 included subjects are shown in Table 1.

Experimental setup

Arm configuration: Subjects were seated in a Biodex (Biodex Medical Systems Inc., USA) seating system with straps across the chest and waist to prevent unwanted movement. The affected arm was positioned in front of the body, with the shoulder in 40° abduction and 20° flexion, and the elbow at 90° flexion. Two wrist positions were used: with a WHO or without a WHO. An experimental WHO was used to maintain the wrist at a position as close as possible to 0° wrist extension (Figure 1).

Setup of markers: In order to capture the hand-opening aperture, 11 infrared emitting markers were placed on the hand and wrist, as shown in Figure 2 by the white dots:

1. Distal part of dorsal distal phalanx of thumb at 1/3 from ulnar side
2. Proximal part of dorsal distal phalanx of thumb at 1/3 from ulnar side
3. Distal part of dorsal metacarpal of thumb
4. Scapoid bone on dorsal side

	Mean (range)
Number of subjects	12
Male/Female	8/4
Age (year)	62 (42-82)
Post stroke (year)	12 (3-30)
Affected side R/L	2/10
FMA	20.5 (10–28)

Table 1: Subject Information.

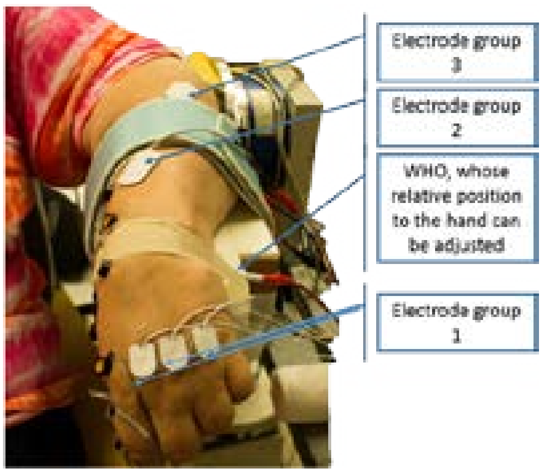

Figure 1: The placement of stimulation electrodes.

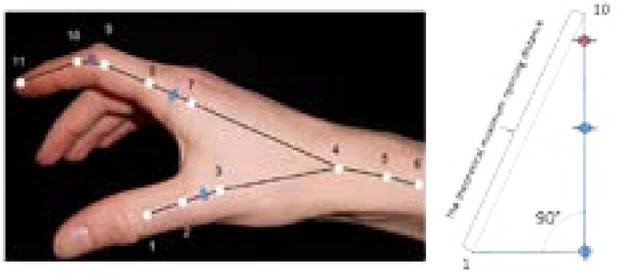

Figure 2: Placement of the Optotrack makers.

5. Distal radius, radial side, 1 cm from styloid process
6. Distal radius, radial side, 2 cm from marker 5
7. Distal part of metacarpal 2, radial side
8. Proximal part of dorsal distal phalanx of dig. 2, radial side
9. Distal part of dorsal distal phalanx of dig. 2, radial side
10. Proximal part of dorsal 2nd phalanx of dig. 2, radial side
11. Distal part of dorsal 3th phalanx of dig. 2, radial side

FES settings: FES electrodes were located to produce maximal finger extension (electrode group 1 in Figure 1), the maximal thumb extension (electrode 2 in Figure 1), and the maximal wrist extension (electrode 3 in Figure 1), respectively. FES was delivered by Compex II (Compex Medical SA, Ecublens, Switzerland) stimulator via surface electrodes (diameter 1 to 3.5 cm, Empi, MN, USA). A bipolar symmetric square wave with pulse duration of 250 µs, delivered at 25 Hz frequency was used. Stimulation amplitude for each muscle was defined as the amplitude that resulted in the maximal desired movement without discomfort to the participant.

Experimental protocol

In following paragraphs, maximal hand opening (MO) was performed actively by subjects in all conditions. The superscript and subscript represent the extensors that were simulated and the use of a WHO, respectively. No superscript or no subscript means that no FES or no WHO was applied.

Subjects were instructed to maximally open their hand under each of the following 6 conditions:

1. Voluntarily maximum hand opening (MO),
2. WHO (MO_W)
3. FES to the finger and thumb extensors (electrodes 1 and 2) with WHO (MO_W^{FT})
4. FES to the finger and thumb extensors (electrodes 1 and 2) without WHO (MO^{FT})
5. FES to finger, thumb and wrist extensors (electrodes 1, 2 and 3) with WHO (MO_W^{FTW}), and
6. FES to finger, thumb and wrist extensors (electrodes 1, 2 and 3) without WHO (MO^{FTW})

All conditions were tested at least three times in a randomized order. Each trial lasted for 6 seconds. In order to avoid muscle fatigue, a rest of at least 1 minute was provided after each trial. The end positions achieved at the fingers and wrist for each of the conditions were

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quantified using the Optotrak 3020 system (Northern Digital Corp, Canada) with a sample frequency of 100 Hz.

Analysis

The two primary measures of interest of this study were:

The amount of finger opening - quantified by the absolute distance between marker 1 and 10 (Figure 2) normalized by the subject-specific theoretical maximum opening distance between these markers. To calculate the subject-specific theoretical maximum distance, we measured piece-wise linear distance between the markers. These piecewise lines include: the length from the marker 10 to the end of intermediate phalanges (the red dot in Figure 2), the length of proximal phalanges (between the red and first blue dots from distal), the distance between metacarpal phalangeal (MCP) joint of index finger and MCP joint of thumb (between the two blue dots in Figure 2), and the distance between marker 1 and MCP joint of thumb (the blue dots close to the thumb). We then theoretically extended the index finger and calculated the distance between the markers 1 and 10 when their angle was 90°, as illustrated in the right side of Figure 1.

The flexion angle at the wrist - determined by the angle between line segment 4-7 and segment 5-6 (Figure 2), during maximum hand opening.

Statistical analysis

Repeated measures of multivariate analysis of variance (RMANOVA) were used to test the effects of FES and a WHO on the two primary measures: finger opening distance and wrist flexion angle. Post-hoc analysis using paired t-test was used to report the significance of the effects ($p<0.05$) or the trend of significance ($p<0.1$).

Results

Figure 3 shows the effects of all conditions on the normalized finger opening distance (left) and on the wrist flexion angle (right). A two-way RMANOVA (independent factors are FES: 3 levels --- Voluntary activation, FES on Finger and Thumb extensors, or FES on Finger, Thumb and Wrist extensors; and whether or not a WHO was used) showed non-significant interaction between using a WHO and FES ($p>0.1$).

Opening distance

The FES conditions demonstrated a clear trend towards significance in enlarging the finger opening distance ($p<0.1$). The post-hoc analysis demonstrated that: 1) when a WHO is used, FES results in a significant difference or a trend towards a significant increase in finger opening distance (MO_W^{FTW}) $p<0.05$, and (MO_W^{FT}) $p<0.1$) compared to voluntary hand opening with WHO (MO_W condition); and 2) when a WHO is not used, the use of FES on finger+thumb+wrist extensors (MO^{FTW}) resulted in the greatest finger opening, achieving approximately 60% of the maximum theoretical opening distance (about 69 mm in average). This increase showed a trend towards significance $(MO^{F}TW)$ $p<0.1$) as compared to voluntary hand opening without WHO.

The RMANOVA analysis showed an overall significant effect of the WHO on finger opening ($p<0.05$). The post-hoc analysis showed that there was a significant reduction in the maximal finger opening distance when using WHO as compared to no WHO (i.e., MO versus MO_W, $p<0.05$, and MO^{FTW} versus MO_W^{FTW}, $p<0.05$).

In order to further investigate whether FES/WHO-assisted hand opening is functionally useful, we investigated the maximal absolute opening distance achieved by using FES/WHO. Since hand opening

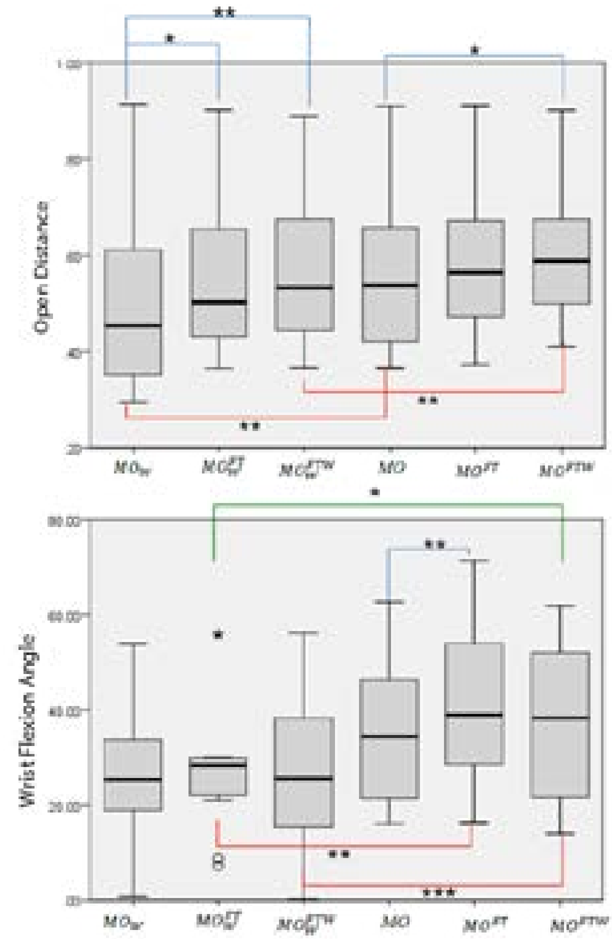

Figure 3: Box plot of normalized hand opening distance (upper plot) and wrist flexion angle (degree, lower plot) under each of the conditions. Significant differences between two paired conditions, reported by a post-hoc t-test, were plotted (* p<0.1, ** p<0.05, *** p<0.01). The blue, red and green lines represent the significant effects of FES, WHO, and FES combined with WHO, respectively. For example, as shown in the upper plot, there is a significant difference in the opening distance between not-using FES and using FES on finger+thumb, both with WHO applied, as marked by the blue line between the first 2 bars from left (p<0.1); and a significant difference in the opening distance between using WHO and not-using WHO, both without FES, as marked by the red line between bars #1 and #4 (p<0.05). The green line marks the comparison between using FES and using WHO to achieve neural wrist position.

achieved by FES-assistance can be more important in subjects who totally lost opening ability as compared to individuals who still retain some voluntary hand control, we divided subjects into 2 groups according to their ability to open their hand voluntarily. Four subjects were unable to voluntarily open their hand more than 2% of maximal theoretical opening distance (about 1.4 mm) and 8 subjects were capable of achieving voluntary hand opening. There was a significant between-group difference in the effect of FES ($p<0.05$) on hand opening distance. The post-hoc test showed that overall FES resulted in significantly larger hand opening in subjects who could not open their hand voluntarily. In this group, the average FES-induced improvement of hand opening was 12% (approximately 8 mm) with the WHO and 15% (approximately 10 mm) without the WHO.

In short, while FES on finger and thumb extensors demonstrated a clear trend of increasing hand-opening distance, the use of WHO significantly reduced the opening distance however with only a 2 mm distance.

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Wrist flexion angle

FES to the finger extensors significantly increased the wrist flexion angle ($p<0.05$) when no WHO was applied. No other significant effect of FES on wrist flexion was found. It is worthy to note that adding FES to the wrist extensors did not significantly change the wrist angle, as compared to the voluntary or WHO alone conditions or to the condition with FES on finger extensors.

The WHO had significant effect on the wrist flexion angle ($p<0.05$). The post-hoc test revealed significantly reduced wrist flexion angle when comparing conditions with and without WHO with the same FES configurations (i.e., MO_W^{FT} $vs.MO^{FT}$ $p<0.05$,and MO_W^{FTW} $vs.MO^{FTW}$ $p<0.01$).

In short, FES to the finger and thumb extensors significantly increased the wrist flexion angle, and FES to the wrist extensor cannot significantly reduce it. The use of WHO has a significant effect of reducing wrist flexion angle ($p<0.05$).

Hand opening while keeping wrist in a slightly extended position

In order to achieve finger extension while keeping wrist extension, we compared the within-subject effect of FES to finger, thumb and wrist extensor without WHO to that of FES only to finger and thumb while combined with a WHO. The effect of these two methods on finger opening distance was not significant ($p>0.2$). However, the WHO combined with FES on finger and thumb condition has a clear trend of significant effect in reducing the wrist flexion angle ($p=0.057$) (Figure 3).

Discussion

Although both FES and WHO have been widely used post-stroke, their combined effect on hand opening has not yet been well investigated. The study of hand opening with the wrist in a neutral position may allow for performance of functional tasks in a more natural way. The feasibility of generating hand opening with a neutral or slightly extended wrist posture either volitionally of with a WHO has not been well explored yet, although reports on the use of FES on overall hand and arm function have been published [14]. Therefore, this pilot study intends to provide useful information for designing new interventions and devices using FES related methods to assist functional hand tasks.

Effects of FES

All subjects reported that hand opening with FES took less effort. Our results demonstrated that FES to the finger and thumb extensors has a clear trend towards significance in increasing hand opening distance ($p<0.1$). The best FES-induced improvement in hand opening was approximately6mm more than voluntary hand opening (57 ± 21 mm). Furthermore, using FES on finger and thumb extensors significantly increased wrist flexion angle ($p<0.05$), which is undesirable during normal hand tasks. Additional FES to the wrist extensor did not reduce wrist flexion angle. This suggests that FES alone, as studied to the wrist, finger and thumb extensors, may not produce hand opening with the wrist in a neutral position.

In order to further investigate the effect of FES on functional hand opening, we examined maximal hand opening distance. We found a significantly larger FES effect in participants who could not open their hand voluntarily ($p<0.05$) as compared to participants who still maintain voluntary hand opening ability. However, the change in opening distance (10 mm) may not be sufficient to enable function. The absolute hand opening distance achieved by FES/WHO-assisted voluntary effort (<10 mm) is in the similar range as reported in previous case studies on 2 moderately to severely impaired individuals [14]. In the same study, a much larger hand opening distance was also reported in a more severely impaired subject [14]. Comparisons to the previous study are necessarily limited however, because the configuration of FES electrodes was not reported [14].

Effects of WHO

Using a WHO significantly reduced the wrist flexion angle. However, it also significantly decreased the finger opening distance by approximately 5% (2 mm as compared to a paired without WHO condition). This is only a small reduction in hand opening that is likely to disappear following more long-term use of FES [15,16].

Choice of FES/WHO for assisting hand opening while keeping the wrist in a neutral position

Our study demonstrated that FES increases finger-opening distance but decreases wrist extension angle, while WHO use slightly decreases finger opening distance, maybe due to the tenodesis effect [17], but increases wrist extension angle. A balance between finger opening distance and wrist extension angle is required for function. Our study results showed FES alone and FES/WHO resulted in similar level of finger opening; however, FES/WHO had a clear trend toward significance in increasing wrist extension. Potential benefits of combining WHO/FES are the elimination of a FES channel targeting the wrist extensors as well as ensured stability of the wrist during performance of functional tasks. Additionally, a previous study reported that FES/WHO use generates a more natural, smoother hand movement [18]. These data therefore suggest that the combination of FES and a WHO may be an effective choice for the future design of assistive devices for hand function post stroke.

Limitations

As a pilot study, a relatively small number of subjects (n=12) were tested. Therefore, some of statistical results did not reach the significant level ($p<0.05$). Instead, our results showed a clear trend of significance, suggesting that future study is warranted. Previous studies had suggested that FES with higher frequency and longer pulse duration might result greater activation levels in target muscles [19]. This suggests that the comparisons of various FES stimulation parameters may merit further investigation. Furthermore, the measurements in our study were undertaken during a single FES session. The effect of an FES training program on effects should be studied [15,16]. Finally, hand opening during proximal arm activities, such as during reaching movements, may alter the effects of FES and a WHO [14,15], and thus should be examined in future studies as well.

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