Elicited upper limb motions through transcutaneous cervical spinal cord stimulation

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Abstract
Objective. Transcutaneous cervical spinal cord stimulation (tsCSC) has been demonstrated to activate the dorsal root and activate targeted muscles. However, it is unclear whether tsCSC can elicit functionally relevant movements of the upper limb for assistive/rehabilitative purposes.

Approach. The current study sought to elicit arm and hand movements by tsCSC by placing an electrode array near the cervical segments of the spinal cord. Anode stimulation current pulses were delivered to the dorsal side at 120 Hz and 30 Hz in separate trials. The elicited joint kinematics were captured using a motion tracking system.

Main results. The results revealed that distal and proximal joint movements can be elicited either independently or synergistically. Specifically, different motions, including flexion and extension of the elbow, wrist, and five digits, can be selectively elicited by adjusting the stimulation parameters, such as stimulation location and stimulation intensity.

Significance. The findings demonstrated the feasibility of the spinal cord stimulation technique in eliciting functional movements of the upper limb. The outcomes also revealed the potential of the tsCSC technique as a promising assistive or rehabilitative method for individuals with impaired function of the upper limb.

1. Introduction

Neurological injuries, such as stroke or spinal cord injury, are the main cause of long-term disabilities in the United States [1]. For example, approximately 70% of individuals after a stroke are left with impaired arm and hand functions [2], partly due to muscle weakness and/or spasticity. The upper limb is fundamental to activities of daily living with the ability to reach and grasp objects. Therefore, individuals with quadriplegia consider regaining arm and hand functions as the foremost to improve the life quality among different motor and sensory functions [3]. Different functional electrical stimulation (FES) techniques have been developed to elicit joint motions and help restore purposeful movements [4, 5].

Compared with the voluntary muscle contraction, conventional FES typically place stimulation electrodes at the muscle belly near the motor points. The elicited muscle activation pattern is not sustainable, because motor units (MUs) are recruited in either a physiologically reversed [6] or a random order [7], and MU activations are highly synchronized. In addition, superficial muscles are mostly activated [8], which can constrain movement kinematics due to the limited activation of deeper muscles [9]. The deeper muscles can be activated using large stimulation current, while dispersed current can also decrease the selectivity of muscle activations.

To address the limitations of conventional FES, multiple electrodes on the muscle belly have been used to delay the fatigue onset by activating different muscle fibers sequentially with a low stimulation frequency [10–12]. Peripheral nerves can also be activated through invasive implantable electrodes [13, 14], which can activate a range of superficial and deep muscles and elicit precise finger movements with a low stimulation current. Recently, the proximal segment of peripheral nerve bundles has been stimulated transcutaneously in order to activate deep muscles. This technique can also lead to a more physiological MU recruitment order through the reflex loop [15]. With high-frequency stimulation, dispersed activation of the muscle can also be observed [16–18]. Functionally, electrical stimulation at the proximal
nerve bundles can elicit dexterous hand grasp [19, 20] and hand open [21] patterns. However, the movement of proximal joints (elbow and shoulder) cannot be elicited.

Coordinated movements of multiple joints including the finger, wrist, and elbow, are common in activities of daily living. When using conventional FES to elicit multi-joint movements in a coordinated manner, multiple electrodes are placed at different muscles from both the forearm and upper arm, and sequential stimulations for different muscles need to be adjusted individually [22]. Moving further upstream from motor points to peripheral nerve bundles and then to the spinal cord, previous studies [23, 24] have demonstrated that transcutaneous stimulation near the cervical spinal cord (tsCSC) can activate the sensory afferents and/or the dorsal roots, which could promote recovery of upper extremity function due to neuromodulation of the spinal circuits [24, 25]. These studies mainly focused on the modulatory effect of the stimulation and therefore large electrodes (e.g. 5 × 10 cm) are typically used to guarantee the activation of the spinal cord. The dorsal roots near the cervical spinal cord involves the axons innervating all the muscles from the upper limb. This anatomical property, however, means that the tsCSC has the potential to elicit contractions of all upper limb muscles, which imposes a challenge to selectively activate different muscles independently to elicit functionally meaningful movements. In a previous study, instead of using a single large electrode, a 3 × 3 electrode array was used to activate different upper extremity muscles by changing the stimulation location [26]. It has been demonstrated that this spinal stimulation paradigm can lead to asynchronized muscle activation pattern with a possibility of activating the spinal and supraspinal pathways [26]. However, it is not clear whether this spinal stimulation paradigm can selectively elicit different functional movements of the upper limb for assistive/rehabilitative purposes.

Accordingly, the current study investigated the feasibility of the tsCSC technique in eliciting different upper limb movements at different joints. Specifically, a stimulation electrode array was placed near the cervical segments of the spinal cord. Anode stimulation current pulses were delivered to the dorsal side of the spinal cord. The evoked upper limb movements were recorded. The results showed that the tsCSC can elicit both distal (finger and wrist) and proximal (elbow) joint movements, such as hand opening/closing and elbow flexion/extension. By adjusting the stimulation parameters (such as intensity and location), these proximal and distal joint movements can be elicited either independently (single joint) or in a coordinated manner (multiple joints). The outcomes suggest that, compared with peripheral nerve or motor point stimulation, tsCSC could be further developed as an alternative neural stimulation approach that can elicit functionally relevant movements in the proximal and distal joints of the arm and hand.

2. Methods

2.1. Experiment

2.1.1. Subjects.

To evaluate the feasibility of the stimulation technique, only individuals with no neurological or musculoskeletal disorders were recruited. Six male subjects with an age from 21 to 34 were tested, and all gave informed consent via protocols approved by the Institutional Review Board of the University of North Carolina at Chapel Hill.

2.1.2. Stimulation paradigm.

A programmable multi-channel stimulator (Multichannel Systems, Reutlingen, Germany) was used to generate the electrical stimuli. The anode and cathode of individual stimulation channels were connected to the rows of a switch matrix (Agilent Technologies, Santa Clara, CA). The columns of the switch matrix were then connected to 12 gel-based electrodes. Each electrode was a 1 × 2 cm rectangle. Nine of them were used as anode and were arranged as a 3 × 3 grid placed near the cervical spinal cord. The placement of the electrode array was determined by the anatomy (i.e. the position of the spinous processes) of each subject. Specifically, the C7 spinous process was first identified by palpating the most prominent cervical spinous process. The position of C5-C8 and T1 were then identified. The 3 × 3 array was placed to cover the area to the right side of the midsagittal plane from C5 to T1 segments to target the right limb (figure 1(a)). The other three electrodes (cathode) were arranged in a 1 × 3 array and placed above the clavicle, approximately 6 cm to the midsagittal plane. Given a relative large distance from the electrode at the skin surface and the targeting neural tissue, the anode electrode grid was placed at the posterior side, similar to the anode transcranial current stimulation protocol, cations (+) accumulate near the anode electrodes, which draw anions (−) a certain distance away from the electrodes but close to the targeted neural tissue. As a result, the depolarization potential can effectively activate the neural tissue. A previous study also showed that asynchronized muscle activation can be elicited through this electrode configuration [26]. The stimulator was controlled using a custom-written MATLAB user interface to change the parameters of the electrical stimuli (such as pulse width, stimulation frequency, and stimulation amplitude), and the switch matrix was also controlled using the same user interface to deliver current to any anode and cathode pairs.

The subjects were requested to put their forearms on a desk in the pronated position and naturally flex the metacarpophalangeal (MCP), the wrist, and the
elbow joints before the stimulation started. A foam cushion was used to support the forearm so that there was enough room for the wrist joint to flex without fingers touching the desk. The width of the monophasic current pulse was fixed to 600 µs based on earlier studies in which the pulse width ranged from 200 µs to 1 ms [24, 27, 28]. The stimulation frequency of 120 Hz and 30 Hz was selected in this study to match the firing rate of afferent fibers in physiological condition [29–31]. A manual searching procedure was first performed to find out the anode and cathode electrode combinations with which single or multiple joint movements can be elicited using the two stimulation frequencies, respectively. The current amplitude was adjusted so that moderate or strong joint range of motions can be elicited. The resultant current amplitude was 5.32 ± 1.70 mA (mean ± standard deviation) and 6.13 ± 1.90 mA for the 120 Hz and 30 Hz trials, respectively across all subjects. In each trial, only one anode and cathode pair was tested and fifteen 3 s stimulation trains were delivered. In order to avoid possible muscle fatigue, 2 s resting intervals were added between stimulation trains. After each stimulation train, the subject was requested to place their upper limb back to the initial position.

2.1.3. Data recording.
Joint kinematic data including the flexion/extension angles of MCP of the five digits, the wrist flexion/extension angles, and the elbow flexion/extension angles were acquired using a motion capture system. Sixteen 6.4 mm diameter retroreflective markers were attached on the back of the hand and individual proximal phalanges to measure the MCP joint angles. Four additional 9.5 mm diameter markers were attached on the posterior side of the forearm and the back of the hand near the wrist to measure the wrist joint angle (figure 1(b)). Another four 9.5 mm markers were attached to segments of the forearm and the upper arm near the elbow to measure the elbow joint angle (figure 1(b)). The 3D positions of the markers were captured using an 8-camera motion tracking system (Optitrack, Natural Point, Inc. Corvallis, OR), and the images were captured with a frequency of 120 Hz.

2.2. Data processing

2.2.1. Elicited motion types.
The calculation of the MCP, wrist, and elbow joint angles are shown in figure 1(b). In order to obtain average joint trajectories of each stimulation trial, 4.5 s segments were extracted from the time series data of individual joint angles (figure 2). Each segment started 0.5 s before and 4 s after the onset of individual 3 s stimulation trains. These segments were then averaged to obtain the average time series of joint angles \(X_j(t), t \in [-0.5, 4]\)\(j = 1, 2, \ldots, 7\) joints). In order to extract the standardized feature vectors that can reflect the range of motion (ROM) of different joints from all subjects, the following procedure was performed for individual trials. First, the resting joint angles \(I_j = \text{ave}(X_j(t)), t \in [-0.5, 0]\) were calculated for individual joints. The operation of \(\text{ave}()\) means calculating the average value. Then, the time \(t_{max}\) corresponding to the maximum joint angle deviation from the initial angle, \(t_{max} = \arg\max [X_j(t) - I_j, t \in [0, 3]]\), was selected. According to the definitions of joint angle (figure 1(b)), if \(X_j(t_{max}) - I_j > 0\) the corresponding joint extended during stimulation, and if \(X_j(t_{max}) - I_j < 0\) the corresponding joint flexed. The maximum joint angle deviation was then normalized with the corresponding full joint ROM relative to the initial joint angle, resulting in the features of different joints:

\[
A_j = \begin{cases} 
(X_j(t_{max}) - I_j)/|I_j - E_j|, & X_j(t_{max}) - I_j \geq 0 \\
(X_j(t_{max}) - I_j)/|I_j - F_j|, & X_j(t_{max}) - I_j < 0 
\end{cases}
\]

(1)
where \(F_j\) and \(E_j\) were the joint angles of full flexion and full extension, respectively. In this case, the normalized joint angle movement ranged from \(-1\) to \(1\) with \(-1, 0, 1\) representing full flexion, no motion, and full extension, respectively. Then, these joint angle movements from all seven joints were pooled together to form the feature vectors of individual trials. In order to identify the different types of motions that can be elicited through the tsCSC, the feature vectors from all subjects and all trials were classified using a hierarchical cluster analysis, which has been used in a previous study [21].
2.2.2. Movement stability.

The stability of the movements elicited through the tsCSC was quantified by calculating the variation of the ROM of different joints. First, the elicited joint ROM was calculated for individual stimulation trains (each with a 3 s duration), which was the absolute difference between the initial resting joint angle and the elicited stable joint angle. The resting joint angle was obtained by averaging the joint angle from 0.5 s to 0 s prior to the stimulation onset, and the elicited joint angle was calculated by averaging the joint angle from 1 to 2.5 s after the stimulation onset. Second, the coefficient of variation (CV) of individual joint ROM was calculated, and then averaged across all joints that had an average ROM > 5% of full joint ROM to represent the overall movement variability. The joints with small ROM were excluded because these joints were considered passive without meaningful evoked movements.

3. Results

Eight types of motions (clusters) were obtained through the cluster analysis (figure 3). The individual lines in the polar plots illustrate the normalized maximum joint angle movement for different types of motions. The results showed that motions of both proximal and distal joints can be elicited through the tsCSC. For example, in motion type 1, 5, and 6, hand opening, i.e. extension of fingers and/or wrist extension were elicited. In motion type 3 and 8, elbow flexion and extension were elicited, respectively. Some functional-relevant motions can also be elicited. For example, motion type 4 involved the flexion of four fingers, elbow flexion, and wrist extension, which can be used as a self-feeding motion. The average trajectories of individual joints for different motion types are illustrated in figure 4. The stimulation train started at 0 s and lasted for 3 s. The joint movements were initiated simultaneously when the stimulation started, indicating concurrent coordinated activation of multiple joints.

The types of motions were illustrated in figure 5(a) for individual subjects. The average number of the type of motion for individual subjects was 4.67 ± 1.21 with a range from 4 to 7. Motion type 3 (elbow flexion) and type 8 (elbow extension) were elicited in five and four out of the six subjects, respectively. Motion type 4 with four finger flexion movement was found in five subjects. The extension of four fingers was found in five subjects (except subject 6). The flexion/extension patterns of individual joints in different types of motions (figure 5(b)) were further analyzed by thresholding the average feature vectors (dark blue lines in figure 3). Specifically, if the absolute value of the normalized joint angle was larger than 0.1, the joint was considered to extend, or flex based on the sign of the normalized joint angle. Otherwise, the joint was considered to be inactive. Most of the types of motions involved elbow flexion. On the contrary, extension was more common for distal joints (fingers and wrist).

Figure 5(c) illustrates the electrode pairs that can elicit the corresponding motion types from three subjects. There was no consistency of the electrode pairs that can elicit the same motions across subjects. For all three subjects, some motions can be elicited via different electrode pairs (subject 1: motion 6; subject 3:...
Figure 3. The normalized maximum joint angle movements (feature values) of different types of motions based on the cluster analysis. The origin of the coordinates represents full flexion, and the inner and the outer rings represent the initial angle and full extension, respectively.

Figure 4. The average joint trajectories of individual joints for different types of motions (clusters). The stimulation strain starts at time 0 and lasts for 3 s. The types of motions are consistent with those shown in figure 3.

motion 3; subject 5: motion 1). Meanwhile, some electrode pairs can elicit different motions when the stimulation intensity or the frequency were changed (figure 5(c)).

Table 1 illustrates the number of trials of different motion types elicited by the two stimulation frequencies (120 Hz and the 30 Hz). Both stimulation frequencies can elicit all eight types of motions,
Figure 5. The distribution of different types of motions across subjects (a) and the flexion/extension patterns of individual joints in different types of motions (b). The types of motions are consistent with those shown in figure 3. The electrode pairs that can elicit different types of motions from subject 1, 3, and 5, respectively (c). The blue rectangles represent the electrode from the anterior side above the clavicle. The red rectangles represent the electrode from the posterior side near the cervical spinal cord. The numbers in the rectangles represent the motion types. The red and blue electrode pairs that have the same number n with the same color indicate that the electrode pair can elicit motion type n. The table to the right side of each array illustrates the stimulation intensity and frequency used to elicit motions from the same electrode pair.

Table 1. Number of trials for different types of motion with the two stimulation frequencies.

<table>
<thead>
<tr>
<th>Motion type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stim. Freq. (Hz)</td>
<td>120</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

and the two stimulation frequencies showed no obvious preference to a specific type of motion. In order to investigate whether the stimulation intensity was different under the 30 Hz and 120 Hz stimulation frequency with the same motion, the current amplitudes of the 30 Hz and 120 Hz trials with the same motion type were extracted for individual subjects and then pooled together for statistical analysis. The results of paired t-test (figure 6(c)) showed that there was a significant difference in the current amplitude between the two frequencies ($t(15) = 6.1922, p < 0.0001$).

Figure 6(a) shows the CV of the joint ROM elicited from the 30 Hz and 120 Hz stimulation trials separately for individual subjects. The CV values were largely located within 0.1–0.4. The averaged CV across all subjects was 0.28 ± 0.22 and 0.30 ± 0.16 for the 30 Hz and 120 Hz trials, respectively. The high CV values, considered outliers, largely came from the trials with small joint ROM. The outlier trial of subject 2 involved three joints with ROM of 7.19°, 5.29°, and 5.15°, respectively. In order to evaluate whether the movement stability differed between the 30 Hz and 120 Hz stimulation frequency, the CV of the 30 Hz and 120 Hz trials with the same motion type were extracted for individual subjects and then pooled together for statistical analysis. The results (paired t-test, figure 6(b)) showed that there was no significant difference of the CV between the two frequencies ($t(15) = −0.6132, p = 0.5489$).

4. Discussion

We investigated the upper limb motions elicitable through the tsCSC technique. The kinematics of the MCP of the five digits, the wrist, and the elbow joints were measured using a motion capture system. We found that the tsCSC approach can elicit different movements of both proximal (MCP joints and wrist) and distal (elbow) joints of the upper limb. This is possible by changing the electrode position and the stimulation intensity. Our results demonstrated that the tsCSC can be used as an alternative approach to generate selective upper limb motions for assistive or rehabilitative purposes.

Movements at the distal and proximal joints can be evoked either independently or in a coordinated manner. For example, motion type 3 and 8 mainly involved the proximal joint (elbow) flexion and extension, respectively, while motion type 5 and 6 mainly showed the distal joint (MCP and wrist)
extension. This indicates that the tsCSC can selectively activate the distal and proximal joints of the upper limb by adjusting the stimulation electrode position relative to the spinal cord. However, individual finger movements were not elicited in this study, possibly because the stimulation location and intensity were manually searched, which was, to some degree, arbitrary. As a result, the neural tissue that can elicit individual finger movements were not activated. Coordinated movements of the proximal and distal joints can also be elicited, which were relevant to activities of daily living. For example, motion type 4 was a self-feeding motion including finger flexion, wrist extension and elbow flexion. The tsCSC technique in this study requires further development prior to clinical applications, but it demonstrates the potential to restore or enhance specific, functionally relevant movements of the upper limbs.

Muscle spasticity is common in a variety of neurological conditions [32], which is manifested as hyper-flexed elbow, wrist, and digits in the upper limb [33]. Spasticity can limit active joint range of motions. A combination of weakness in extensor muscles and spasticity in flexor muscles severely limits patients’ ability of extending the arm outward and opening hand [34–36]. Therefore, when spasticity occurs, practicing hand opening and elbow extension may be limited. It is promising that the tsCSC technique can elicit extension of the MCP joints of all five digits, the wrist, and the elbow, demonstrating the potential as a technique to help practice hand opening and elbow extension movements, in order to alleviate the effect of spasticity.

In this study, the average stimulation intensity was 5.73 ± 1.83 mA across all subjects, and the low stimulation intensity could elicit multiple joint movements with a moderate to strong joint range of motions. On the contrary, the conventional FES targeting the motor points typically requires a substantially higher stimulation intensity, which ranges from 20–40 mA [37, 38]. Since the distal portion of the nerves can be at different depths of the muscle, a high stimulation current amplitude is needed in conventional FES to activate deep motor axons and therefore, produce meaningful joint movements. In contrast, the diameter of the dorsal and ventral roots near the cervical spine is up to 4.6 mm [39]. Therefore, sufficient motor and/or sensory fibers that innervate a large number of muscle groups can be activated to generate meaningful movements even with a small stimulation intensity. The low current intensity can have two-fold benefits. First, it can help improve the adoption of the spinal electrical stimulation approach because of a reduced discomfort that is induced by the electrical stimulation. Second, the low current can also help reduce the power consumption, which can help develop a more portable stimulation system with a small battery size or a longer recharging cycle.

In conventional FES, the change in muscle geometry due to limb movement may affect the response to stimulation. A previous study has reported that a 1.5–2 cm shift in the location of the innervation zone on the biceps brachii is associated with changes in the elbow joint angle [40]. This may shift the optimal stimulation location that can elicit maximum muscle contractions during elbow flexion and extension [37]. On the contrary, the stimulation electrodes were placed near the spinal cord of the dorsal side or above the clavicle. The electrode locations were not influenced by the motion of upper limbs and muscle contractions. Therefore, the stimulation near the spinal cord had the potential to elicit more stable joint movements during dynamic motions compared with conventional FES techniques.

The average CV values that quantify the stability of elicited motions were approximately 0.2, which was comparable with the motor variability of voluntary reaching movements [41]. However, the CV was higher for subject 6, and several trials with larger CV values were also observed for the other subjects. There might be several factors resulting in large CV values in some trials. First, even though subjects were requested to keep the position of their upper limbs consistent across all intervals between stimulation trains, the actual position can be different across intervals. Therefore, the variation of ROM can be

![Figure 6](image_url). The box plots of the coefficient of variation (CV) of the joint kinematics of individual subjects (a). The CV from trials with the same motion under the 30 Hz and 120 Hz stimulation frequency (b). The current amplitude from the trials with the same motion under the 30 Hz and 120 Hz stimulation frequency (c). The error bars represent the standard error. *, p < 0.0001.
enlarged. Second, most of the passive joints can be excluded using the threshold of 5% full ROM from the CV calculation. However, there might be some joints with low movement amplitudes but still above the threshold. The variation of the ROM from these joints can be large, resulting in large CV values and an overestimation of the overall CV value across all joints. In the current study, in order to selectivity elicit different motions, small electrodes were used to activate a subset of axons in the bundle without activating others. However, if the spinal stimulation was intended to modulate spinal excitability, as in most previous SCI studies [24, 25, 42], a larger electrode was used mainly because the large size of electrodes can guarantee the activation of the spinal circuitry. Therefore, the specificity of these techniques is low, compared with our study. It remains whether a better rehabilitation outcome can be obtained if precise excitability modulation of the spinal circuitry is performed.

The results showed that there was no consistency with respect to the electrode pairs that can elicit the same motion type across subjects (figure 5(c)). There might be several reasons for this. First, the position of the electrodes above the clavicle was, to some degree, arbitrary, and can substantially influence the distribution of the electrical current field in the tissue across subjects. Second, the electrode positions near the spinal cord were mainly determined by finding the C7 spinous process using the conventional method of palpating the most prominent cervical spinous process. However, it is possible to falsely identify the C6 as the C7 spinous process using this palpation method as shown in a previous study [43]. Third, the stimulation intensity can also substantially influence the axons/neurons that are activated. Due to the manual searching of the electrode pair during the experiment, the selection of the stimulation intensity was arbitrary. This could also contribute to the inconsistencies of the motions elicitable with the same electrode pairs across subjects. Even though no consistent electrode positions were found, the tsCSC method still has a promising clinical application with further development. An automatic searching procedure can be performed to find out all the possible combinations of electrode pairs and stimulation parameters within a short time for individual subjects, which has been demonstrated in our previous study on the proximal nerve stimulation [19, 44]. In addition, an automatic searching strategy to identify the available motions is necessary when the tsCSC technique is used across days, given that the elicited motions can change after donning-doffing of the stimulation electrodes. The automatic searching strategy as well as the consistency of elicited motions across days need to be investigated in further studies. It is interesting to find that the same motion type can be elicited through different electrode pairs for the same subject. This redundancy can possibly help to reduce muscle fatigue by alternating the stimulation locations if different stimulation locations result in the activation of different muscles or muscle regions, which will be investigated in the future. The shoulder movement was not analyzed in this study, mostly due to the constraints of our motion capture system, which was configured to capture small finger and wrist joint movements in a confined space. In addition, the forearm pronation/supination movements was not captured, largely because hand opening/closing movements were the main targets for the distal joints. However, both shoulder movements and forearm pronation/supination were observed during the stimulation trials in a number of subjects. Since an impaired shoulder function can reduce the reaching work area [45], and an impaired forearm supination is also common after CNS injuries [46], further studies are needed to quantify the shoulder and forearm pronation/supination movements with the tsCSC stimulation. In addition, an automatic searching strategy can be expected to find all possible combinations of electrodes and stimulation parameters in order to elicit more functional upper-limb movements.

Lastly, only neurologically intact individuals were recruited. The results mainly showed that the tsCSC using the electrode array can selectively elicit different functional motions of the arm and hand. Previous work has shown that upper limb muscles can be activated through the spinal cord stimulation in individuals with a spinal cord injury (SCI) [24]. However, since the excitability of spinal circuitry may be altered in individuals with stroke [47] or spinal cord injury, the application of the tsCSC method on different neurological conditions, can be different. The goal of the tsCSC method was to selectively elicit different functional upper-limb motions for rehabilitative/assistive purposes. For stroke survivors, we speculate that the tsCSC method can be used directly for most stroke survivors. However, it should be noted that for individuals with spasticity that partly results from the hyperexcitable reflex pathways and disinhibition of supraspinal pathways [48], the muscle activation pattern and the elicitable motions need to be verified in further studies, considering that the tsCSC can elicit motions not only by activating the sensory nerves/dorsal roots but also by involving some spinal-supraspinal circuitry [26]. Similar application of the tsCSC on SCI individuals can also be performed below the level of injury. Depending on the degree and position of SCI, the types of motion elicitable via tsCSC need to be verified.

5. Conclusions

The feasibility of eliciting the finger, wrist, and elbow flexion/extension movements using a transcutaneous stimulation method near the cervical segments of the spinal cord was investigated. The results show
that the distal and proximal joint movements of upper limb can be elicited either independently or synergistically. The different motions can be selectively activated by changing the stimulation parameters, including the stimulation electrode location and stimulation intensity. Since tsCSC can induce reflex activities through the central pathway [23], the motions elicited by the tsCSC method might be more fatigue-resistant compared with conventional FES. With further development, the tsCSC technique can potentially become a more attractive method for either rehabilitative or assistive purposes for individuals with paralyzed upper limb muscles after CNS injuries.

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