

Development of network-based multichannel neuromuscular electrical stimulation system for stroke rehabilitation

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Abstract—Neuromuscular electrical stimulation (NMES) is a promising assistive technology for stroke rehabilitation. Here we present the design and development of a multimuscle stimulation system as an emerging therapy for people with paretic stroke. A network-based multichannel NMES system was integrated based on dual bus architecture of communication and an H-bridge current regulator with a power booster. The structure of the system was a body area network embedded with multiple stimulators and a communication protocol of controlled area network to transmit muscle stimulation parameter information to individual stimulators. A graphical user interface was designed to allow clinicians to specify temporal patterns and muscle stimulation parameters. We completed and tested a prototype of the hardware and communication software modules of the multichannel NMES system. The prototype system was first verified in nondisabled subjects for safety, and then tested in subjects with stroke for feasibility with assisting multijoint movements. Results showed that synergistic stimulation of multiple muscles in subjects with stroke improved performance of multijoint movements with more natural velocity profiles at elbow and shoulder and reduced acromion excursion due to compensatory trunk rotation. The network-based NMES system may provide an innovative solution that allows more physiological activation of multiple muscles in multijoint task training for patients with stroke.

Key words: assistive technology, body area network, distributed stimulator system, motor function recovery, multijoint movement, multimuscle activation, muscle synergy, neuromuscular electrical stimulation, proprioceptive afferents, stroke rehabilitation.

INTRODUCTION

Recovering motor functions lost due to lesions in the brain of patients with stroke remains a challenge for both rehabilitation researchers and clinical therapists. Assistive technologies have been developed and used in clinical training of patients with stroke for recovery of motor functions [1–9]. Neuromuscular electrical stimulation (NMES) has been used in the clinic to provide the necessary drive to paretic muscles by directly activating the peripheral nerve,

Abbreviations: AD = anterior deltoid, ARM = advanced reduced instruction set computer machine, BI = biceps, CAN = controlled area network, DAC = digital to analog converter, DC-DC = direct current to direct current, DSU = distributed stimulator unit, EMG = electromyography, FDA = U.S. Food and Drug Administration, FES = functional electrical stimulation, FMA = Fugl-Meyer Assessment, GUI = graphical user interface, MCU = microcontroller unit, MU = master unit, NMES = neuromuscular electrical stimulation, PD = posterior deltoid, SCI = spinal cord injury, TRI = triceps, VCCS = voltage-controlled current source.

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innervating muscles both intramuscularly and transcutaneously [3,10–11]. Clinical studies have shown that NMES therapy could achieve a measurable level of recovery in motor functions even with stimulation of a few muscles involving single-joint movements [12–19]. NMES can improve central excitability to promote motor learning [20] and can effectively improve muscle strength and functional movement through repeated exercise training [21–24]. Clinical studies have been conducted to investigate effective paradigms of motor rehabilitation and to improve the mobility of patients with stroke using NMES [14,16,25–28]. Other studies have reported that patients with stroke have shown improved hand opening and closing movements after 12 wk of training with electrical stimulation [29].

The central neural mechanism of recovery of motor function through NMES is becoming clear. It is hypothesized that proprioceptive and sensory afferents arising from induced movement trigger long-term plastic reorganizations in the brain so that new motor control programming is learned in the course of rehabilitation training [30–38]. However, recent randomized clinical trials in single-joint tasks did not reveal a significant performance difference among electromyography (EMG)-triggered NMES, cyclic NMES, or sensory stimulation [39–41]. It is possible that these modalities of NMES therapies elicited simple and similar patterns of proprioceptive afferents. Multijoint tasks may be able to generate richer and more physiological proprioceptive information for long-term plastic changes in the brain. Repetitive motions at multiple joints should elicit greater amounts of proprioceptive afferents than those involving a single joint and thus may enhance the propensity of motor function recovery [2,42].

Devices for electrical stimulation of muscles with surface and implanted electrodes have been developed and implemented in a variety of clinical applications in the past decades [10–11,43–51]. The NeuroMove 900 (Stroke Recovery Systems Inc; Littleton, Colorado) has been approved by the U.S. Food and Drug Administration (FDA) and can utilize EMG signals detected from paretic muscles to trigger a pattern of electrical stimulation [47]. There are other similar FDA-approved commercialized EMG-functional electrical stimulation (FES) systems on the market, such as the Care ETS (Care Rehab and Orthopaedic Products Inc; Melean, Virginia), Biomove 3000 (Curatronic Ltd; Heshmonayim, Israel), and Ness Handmaster (NESS Ltd; Raanana, Israel) [48]. Each one of these commercial devices is designed to achieve a single-

joint motor function in rehabilitation. More sophisticated devices have also been developed to restore paralyzed movements for patients with spinal cord injury (SCI) and stroke. The Freehand System (NeuroControl Corporation; Cleveland, Ohio) [49], an eight-channel implanted system, is designed to stimulate paralyzed muscles of the upper limb to restore hand function for patients with SCI or stroke. Recent advances in NMES technologies have moved toward network systems based on wireless communication. These devices include an implanted FES system [30,45], implantable BION (bionic neuron) system with injectable units of wireless communication [50–51], and surface FES system with wireless distributed network [52]. Those systems are dedicated to achieving functional restoration in patients with SCI or chronic stroke.

The purpose of this research is to develop a multi-channel NMES assistive device based on a network structure, which will allow patient-specific stimulation of a group of muscles for motor function recovery, along with programming to implement advanced control algorithms for multijoint movement training paradigms. In addition, the system is also designed for early intervention and continued home rehabilitation for patients post-stroke, which is considered more and more important to functional recovery [53–55]. Thus, we designed the assistive NMES system to meet the following requirements: (1) capable of multimuscle stimulation; (2) easy to program and reliable to use; (3) portable for home use in daily training; and (4) compatible with other modalities of intervention, such as robotics. To satisfy these requirements, we designed a distributed surface NMES system based on the body area network structure. In this article, we present the design and test of a prototype of the distributed NMES system. In addition, the surface NMES system can be applicable to patients with acute stroke in early intervention as well as for deployment to home rehabilitation. Design of the system was presented in conference proceedings elsewhere [56–57]. This article presents the development and testing of the system as well as the results of pilot experiments in nondisabled subjects and subjects with stroke.

METHODS

General Design of System Architecture

Figure 1 shows a three-tier structure of the network-based NMES system. The first level includes a graphical

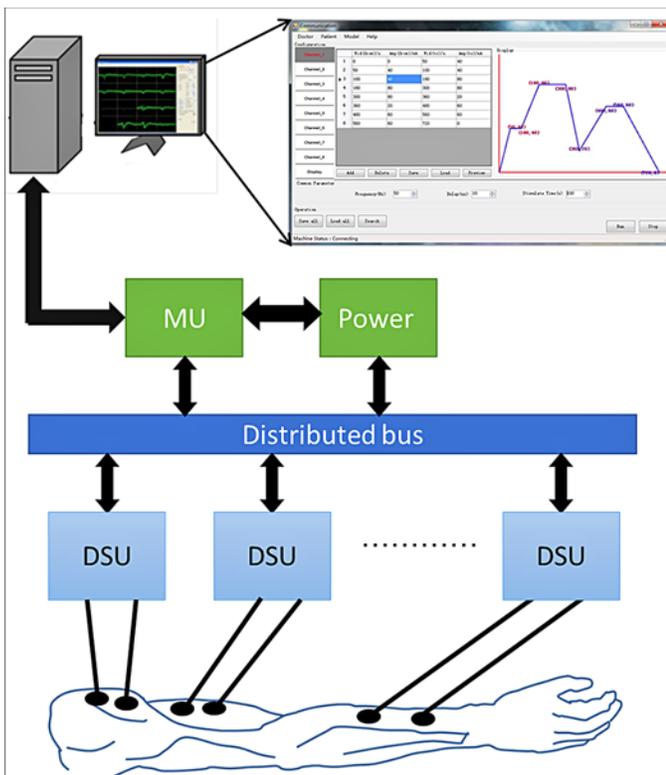


Figure 1.

Backbone structure of network-based neuromuscular electrical system. Top: Graphical user interface that allows therapists to specify stimulation patterns and patient data. Middle: Network controlled by master unit (MU) that translates specified stimulation patterns into parameters to distributed stimulator unit (DSU). Bottom: Muscle and electrode interface that receives stimulation via surface electrodes placed at different positions on arm. Each pair of electrodes is connected to DSU controlled by MU for one channel of muscle stimulation. Multiple DSUs can be attached to network to achieve multiple channels of muscle stimulation.

user interface (GUI) designed for therapists to set stimulation patterns conveniently and a database that runs in the background to handle the patient information in the host computer. The second level is the master unit (MU), which works as the communication and control hub of the network-based NMES system. The third level encompasses a set of stimulators, the distributed stimulator units (DSUs), that performs specific tasks of stimulation prescribed to the DSUs. The DSUs and the MU are linked by a controlled area network (CAN) bus, which is widely used in industrial applications and proven to be a high-speed and reliable communication bus.

This system is customized to have two working modes: supervised mode and independent mode. In supervised mode, the therapist controls the system operation with the host computer. The therapist sets and adjusts the stimulation profile to obtain a satisfactory movement through the GUI. The stimulation profile is downloaded to the MU via the host computer. In independent mode, the temporal profiles of stimulation parameters are preset by the therapist and saved in the MU. Patients can use the independent mode of the NMES system to initiate stimulation during training. This mode of operation allows the patient to receive uninterrupted therapy at home remote to a clinic or hospital.

Design of Graphical User Interface

The software package of the host computer includes a custom-designed GUI, a database of patient and therapy history, and a protocol of serial data transmission. The GUI is designed to facilitate the physical therapist setting up stimulation parameters and observing specified patterns of stimulation (**Figure 1**). Three parameters of stimulation need to be specified for each muscle, i.e., stimulation frequency, pulse amplitude, and pulse width. The stimulation frequency is often fixed throughout the stimulation once chosen. The profile of pulse amplitude or pulse width must be specified. In pulse amplitude modulation, the pulse width is fixed and the pulse amplitude is adjustable. While in pulse width modulation, the pulse amplitude is fixed and the pulse width is adjustable. The stimulation patterns are transmitted to the MU by a “send” command. After receiving a “transmission success” echo signal from the MU, the therapist can then initiate and terminate the prescribed stimulation by sending a “start” or “stop” command.

A database is designed to save the patterns of stimulation prescribed by the therapist. Stimulation parameters can be modified at a later time to follow rehabilitation progress. With this database, patient information, history of stimulation therapy, and rehabilitation prognosis can be stored and recalled to monitor rehabilitation progress.

Design of Master Unit

The MU, composed of an advanced reduced instruction set computer machine (ARM) chip, 64 Mb flash store chip, and 3.2 in. liquid crystal display, is the hub of communication and control of the network-based NMES system (**Figure 2**) in which the MU controls data transmission to and from the DSUs and action of stimulation

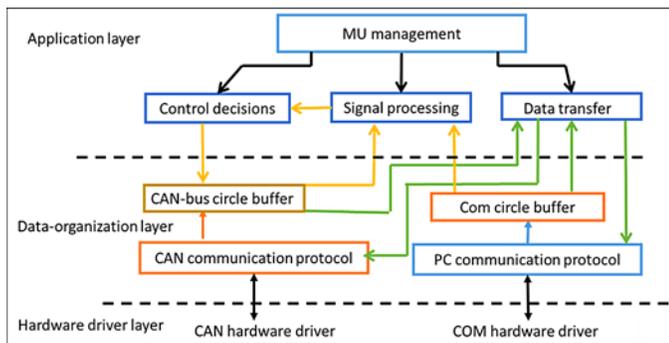


Figure 2.

Firmware logic of master unit (MU) for device communication, data transmission, and operation management. Core of MU firmware includes application layer (in this layer, control method could be planned), data-organization layer in management of simulation profile data, and hardware driver layer that controls stimulators. MU uses “com circle buffer” to receive stimulation profiles from graphical user interface installed in clinic personal computer (PC) and gets start or stop order from same software directly. MU decodes stimulation profiles to stimulation parameters and puts them into “CAN-bus circle buffer.” When stimulation is executed, these parameters are sent to corresponding distributed stimulator unit. CAN = controlled area network, COM = component object model.

through a serial bus. Each DSU acts as one channel of stimulation and generates stimulation pulses that pass through a pair of electrodes. Stimulation is instead initiated by the MU’s action command to the DSUs.

A three-layer structure of the microcontroller unit (MCU) firmware is implemented to achieve the following functions: an application layer at the top, a data-organization layer in the middle, and a hardware driver layer at the bottom. The application layer handles the MU operation and management and is composed of four modules: MU management, control decision, signal processing, and data transfer. The MU management judges the system mode and switches the MU to one of the two working modes. In supervised mode, only the data transfer module is activated and the control decision and the signal processing modules are disabled. The system is controlled by the host computer, and the MU works as a communication hub. In independent mode, the MU management activates control decision and signal processing modules and disables data transfer module. The data organization layer includes communication data buffers and CAN bus protocols. Communication data buffers are two FIFO (first in, first out) ring buffers that can

provide efficient and reliable data access. The CAN bus communication protocol ensures real-time system operation and control. These modules form the MU firmware and ensure that the system performs with high-speed and safe states.

Design of Distributed Stimulator Unit

The DSU is designed to satisfy the following requirements: high reliability, minimal weight, and low power consumption. Although large-scale, high-performance, low-power integrated circuits can be acquired commercially, small-scale, high-performance surface stimulators that satisfy these requirements are not available. Thus, one of the important tasks is to design and develop surface stimulators that can be used in a portable NMES system.

General specifications of the stimulator module are the real-time ability to independently program a wide range of stimulation parameters: pulse amplitude, pulse width, interpulse delay, and pulse frequency. The range of amplitude is from 0 to 50 mA (with a resolution of 1 mA). The pulse width is from 0 to 0.5 ms (with a resolution of 1 μ s). The interpulse delay is from 10 to 100 μ s (with a resolution of 1 μ s). The stimulation frequency can be varied from 8 Hz to 1 kHz (with an increment of 1 Hz). Each stimulator supports two outlets for a pair of stimulation electrodes.

The DSU architecture includes basic modules of stimulator function: (1) a power boost converter (**Figure 3**) that lifts a low battery voltage to the high voltage required for surface stimulation, (2) a current output module that produces a biphasic current pulse with a digital to analog converter (DAC) (**Figure 4**), (3) a monitoring circuit that supervises the operating status of the DSU, and (4) an MCU that controls all DSU operations. A STM32F103RC (STMicroelectronics; Geneva Switzerland) was chosen as the MCU, which is based on the ARM Cortex-M3 32-bit core. The three main modules of DSU design are described in the next sections.

Current Output Stage

The DSU current output stage design is based on an H-bridge circuit (**Figure 4(a)**). The H-bridge circuit has two switches (T_1 and T_2) controlled by IO_1 and IO_2 , and two voltage-controlled current sources (VCCSs) (T_3 and T_4) controlled by An_1 and An_2 . T_1 and T_2 are 2SC1477 transistors, and T_3 and T_4 are D1138 transistors. All transistors have the capacity to work with large currents. The H-bridge circuit can output a biphasic current pulse with high

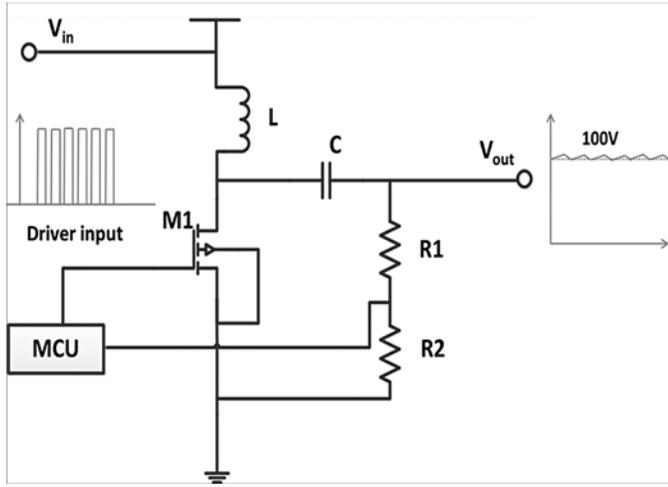


Figure 3.

Design of direct current to direct current circuit. Input voltage (V_{in}) is 24 V, and output voltage (V_{out}) could be raised up to 100 V depending on external impedance between stimulation and return electrodes of stimulator. Values for conductance (L), capacitance (C), resistor 1 ($R1$), and resistor 2 ($R2$) are 1,000 μH , 470 μF , 10 M Ω , and 10 K Ω , respectively. MCU = microcontroller unit.

precision in amplitude and deliver an arbitrary stimulation waveform with balanced charge injection in two phases.

The two switch signals (IO_1 and IO_2) operate synergistically to generate biphasic stimulation pulses (**Figure 4(c)**). **Figure 4(b)** shows the three states in the H-bridge operation. In the first state, all switches are off to make sure that there is no current flow to the load, i.e., the electrode and tissue interface, and the output circuit isolates patients from the high-voltage power supply. In the second and third states, the current output stages deliver the opposite direction currents, whose amplitude is determined by VCCS of the DACs, according to—

$$I_i = \frac{V_i}{R_i}, \quad (1)$$

where $i = 1, 2$; V_i = DAC output; R_i = precision resistance; and I_i = stimulation current. The DAC output varies from 0 to 2.5 V (V_i , **Figure 4**), regulating a current amplitude output from 0 to 50 mA. In our design, a 10-bit DAC (TLV5626, Texas Instruments; Dallas, Texas) with 9-bit data resolution is used as the programmable input voltage source for linear control of the current amplitude. The current resolution obtained is thus $50 \text{ (mA)} / 2^9 = 0.097 \text{ (mA)}$, resulting in a high resolution of regulated current source.

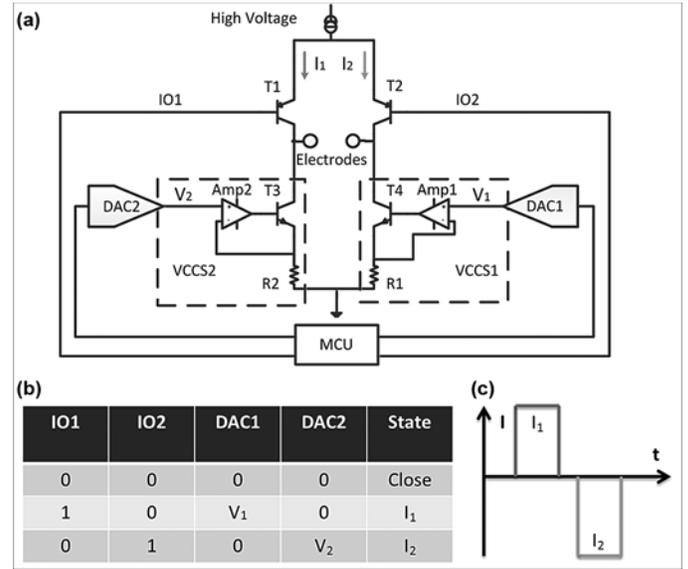


Figure 4.

Output stage circuit and its operation mode. **(a)** Schematic diagram of H-bridge output. **(b)** Logic relation between S_1 to S_4 and I_1 to I_2 . **(c)** Biphasic stimulation current waveform generated by current regulator. Amp = amplitude, DAC = digital to analog convertor, I = stimulation current, IO = switch signal, MCU = microcontroller unit, R = precision resistance, S = switch, T = transistor, V = DAC output, VCCS = voltage-controlled current source.

Power Booster Circuit

To meet the portability requirement, a small-scale, lightweight direct current to direct current (DC-DC) boost converter was designed for the DSU using an inductor-capacitor charging circuit (**Figure 3**). In this design, the driving input to the DC-DC boost converter is a train of high-frequency pulses of 120 to 160 kHz. An MCU monitors power output of the DC-DC converter. If the power output falls below the required level of 100 V, the MCU increases the frequency of driving pulses to increase power output. The output voltage of the boost converter is calculated as follows:

$$\frac{V_{out}}{V_{in}} = 1 + \frac{V_{in} D^2 T}{2LI_{out}}, \quad (2)$$

where V_{out} = output voltage (100~120 V), I_{out} = output current (0~50 mA), V_{in} = input voltage (24 V), L = conductance (1,000 μH), T = period of driver input ($6.25 \times 10^{-6} - 8.3 \times 10^{-6}$ s), and D = duty cycle (80%).

Communication Circuit

Communication circuit design focused on reliability of data transmission. The TJA1050 (NXP Semiconductors Netherlands BV; Eindhoven, the Netherlands) was chosen as the CAN bus chip. The TJA1050 provides 1Mb/s maximum data transfer rate and has high communication reliability with a low error rate. The CAN bus with the photoelectrical isolator (6N137, Arago Technologies; San Jose, California) guarantees isolation between the DSU and other circuits of the system, which can protect the patient from injury. This design satisfies the medical application safety requirements.

Monitor Circuit

To monitor the behavior of the circuit in real-time for safe stimulation, output voltage is monitored. When the DSU is idle, this module keeps no current flowing between the two electrodes. When the DSU performs stimulation, this module enforces an upper-limit stimulation current of 50 mA to prevent injury to patients. It keeps stimulation current below the upper-limit value of stimulation. If there is an operational error, the monitor circuit interrupts the MCU for error handling.

Circuit and System Tests

The prototype multichannel NMES system was constructed and tested to verify that circuits and communication protocols meet the performance requirements. In the circuit test, the waveform of stimulation current between the electrodes was measured to make sure that a rectangular, biphasic current pulse was generated reliably from the stimulator (DSU). In the system test, the temporal profiles of stimulation current were compared with the specified patterns of stimulation. In the two sets of testing, a 2k Ω resistor was used to model the tissue resistance between stimulation electrodes. A National Instruments (Austin, Texas) data acquisition card with a sampling rate of 1 MHz was used to record voltage across the resistors.

Experimental Test with Human Subjects

Subjects

The NMES system was first tested in nondisabled subjects, then in subjects with stroke, for safety and feasibility to elicit multijoint movements. Three nondisabled subjects were recruited initially and four right-handed subjects with stroke were recruited in a follow-up test (Table 1). The subjects with stroke had Fugl-Meyer

Assessment (FMA) scores between 10 and 30, with a mean \pm standard deviation value of 19.8 ± 5.0 (full FMA score = 66). These subjects showed no or mild spasticity with a poststroke time of 1 mo (stroke subject B), 3 mo (stroke subject A), 8 mo (stroke subject C), and 10 mo (stroke subject D).

Experimental Setup

Figure 5 shows the experiment setup, in which the subject sat in front of a wooden table with his or her hand and forearm supported by a fiberglass apparatus to provide support against gravity (Figure 5(a)). The fiberglass apparatus was mounted on a base with plastic ball-bearings that moved on the lubricated surface of a plastic plate. Thus, the subject's shoulder, elbow, and wrist joints could move freely. The wooden table height was adjusted to permit the subject to place his or her right arm on the table at a comfortable horizontal plane. Self-adhesive, flexible electrodes normally used for transcutaneous stimulation in physical therapy were used, which had gel-based contact with the skin. The square-shaped electrode had an area of 25 cm². Six muscles, or a subset of them, were stimulated, including anterior deltoid (AD), posterior deltoid (PD), triceps (TRI), biceps (BI), and wrist extensors. Two multijoint movements were planned: (1) extension of multiple joints with stimulation of PD, TRI, and wrist extensors and (2) flexion of multiple joints with stimulation of AD, BI, and wrist flexors. Kinematic information of movement was recorded with the Motion-Monitor™ II system (Innovative Sports Training Inc; Chicago, Illinois). Five magnetic sensors were placed on the subject's arm and body at the hand, right forearm, right upper arm, right shoulder, and neck. Joint movements of

Table 1.
Subject information.

Subject	Sex	Age (yr)	Height (cm)	Weight (kg)
Nondisabled				
Subject A	Male	28	170	65
Subject B	Male	25	168	65
Subject C	Female	25	166	50
Stroke				
Subject A	Male	50	175	80
Subject B	Male	55	160	75
Subject C	Male	55	170	75
Subject D	Male	60	175	80

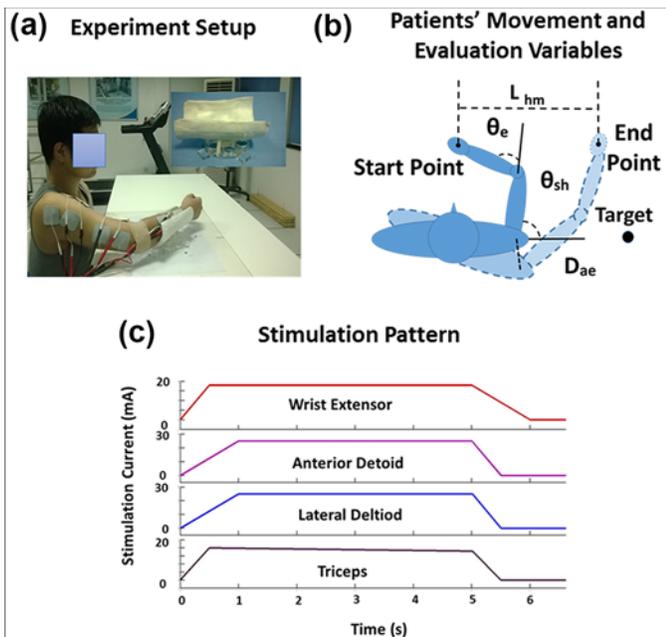


Figure 5.

Human experimental design and setup. **(a)** Experiment is performed with subject's arm supported by fiberglass cast on horizontal glass plane. Two pairs of electrodes are allocated on target arm, with one pair on biceps and another pair on triceps. Under stimulation of two pairs of electrodes, arm is able to move freely on glass surface. **(b)** Subjects with stroke are asked to move arm from start point to target as fast as possible. Four evaluation variables are defined to assess quality of movement: hand movement (L_{hm}), elbow angle (θ_e), shoulder angle (θ_{sh}), and acromion excursion (D_{ae}). **(c)** Stimulation pattern of stroke subject A is shown. Four muscles are stimulated in experiment. Other three subjects with stroke have similar stimulation pattern. **Table 3** shows values of stimulation parameters.

the wrist, elbow, and shoulder and trunk rotation were recorded during multimuscle stimulation (**Figure 5(b)**). The sampling rate was set at 120 Hz, which was sufficient for capturing dynamic contents of movement.

Experimental Protocol

The first experiment was to establish a procedure of setting up stimulation parameters for each muscle: (1) threshold current (or pulse width), at which the individual muscle was activated but no visible movement was produced; (2) movement onset of muscle stimulation, at which visible movement of the arm was induced by stimulation; and (3) uncomfortable sensation of muscle stimulation,

where subjects started to feel uncomfortable prickling with the stimulation intensity. Stimulation parameters in later experiments were bounded between threshold and uncomfortable values (**Table 2**).

In the second experiment, multijoint movements were actuated using the network-based NMES system. In nondisabled subjects, a single muscle was stimulated to check whether a movement could be elicited with stimulation amplitudes between the threshold and uncomfortable limits identified previously. The stimulation pulse frequency was fixed at 25 Hz and pulse width fixed at 90 μ s for all subjects. The range of amplitude modulation was then delineated between the threshold value and the value evoking an uncomfortable prickling sensation in three subjects. The maximal current amplitude that evoked a prickling sensation was measured at the largest pulse width value of 110 μ s.

In nondisabled subjects, two sets of multijoint movements were performed, and each was repeated seven times. In each experiment, programmed stimulation patterns were randomly selected to stimulate muscles. Subjects were not aware which movement was being performed. A rest period of 1 min was allowed between successive tests to prevent muscle fatigue.

In subjects with stroke, a multijoint task involving shoulder, elbow, and wrist extension was performed. Four muscles were stimulated: AD, PD, TRI, and wrist extensor. We programmed the stimulation pattern as shown in **Figure 5(c)**, and the stimulation frequency and pulse width were set at 25 Hz and 100 μ s, respectively. **Table 3** shows the current amplitude values. Stimulation-elicited movements were repeated five times in each subject with stroke. Between two movements, they had a rest of 2 min in order to avoid muscle fatigue due to stimulation.

Table 2.

Limits of stimulation parameters (in microamperes) of nondisabled subjects.*

Muscle	Subject A		Subject B		Subject C	
	I_{th}	I_{pain}	I_{th}	I_{pain}	I_{th}	I_{pain}
Anterior Deltoid	17	22	15	21	15	23
Posterior Deltoid	16	22	16	22	16	24
Triceps	14	19	7	16	10	15
Biceps	6	10	10	15	6	12
Wrist Flexor	8	14	6	12	6	13
Wrist Extensor	7	14	6	13	7	15

*Single measurement was taken with increasing amplitude of stimulation pulses for movement threshold (arm movement was detected [I_{th}]) and pain threshold (prickling sensation was perceived [I_{pain}]) in nondisabled subject tests.

Table 3.

Amplitudes (in microamperes) of stimulation current used in subjects with stroke.*

Muscle	Subject A	Subject B	Subject C	Subject D
Anterior Deltoid	25	20	28	30
Lateral Deltoid	25	20	28	30
Triceps	20	22	25	32
Wrist Extensor	18	18	18	18

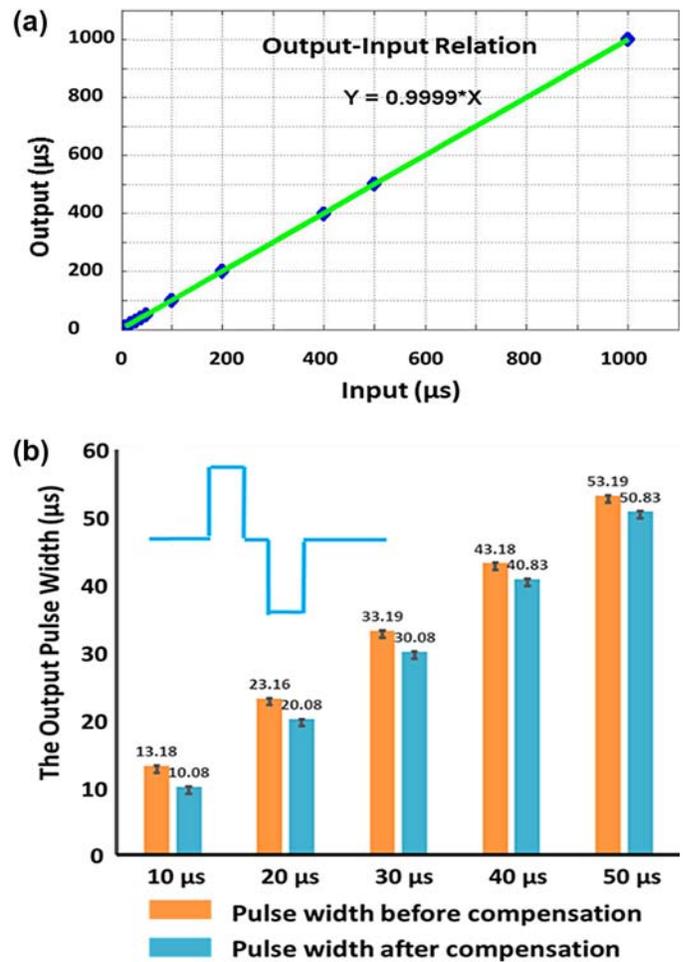
*All subjects with stroke had mild to strong spasticity in arm flexor muscles. Thus, no spastic flexor muscles were stimulated, and only extensor muscles were activated in these tests. At these amplitudes of stimulation, all subjects reported no pain sensation.

Before NMES sessions, the largest range of voluntary movement that a subject with stroke could achieve was measured. The subjects were asked to perform the designed multijoint extension movement task voluntarily and repeat the task 15 times. In the following tests, subjects with stroke were asked to stay in a relaxed state, and electrical stimulation was applied to the muscles by the distributed NMES system. The stimulation pattern was generated based on those obtained in nondisabled subjects performing similar multijoint extension movements. Stimulation frequency and pulse width value were also similar to those obtained from nondisabled subjects. The duration of stimulation was, however, extended to 6 s due to the muscular weakness of subjects with stroke.

RESULTS

Accuracy of Distributed Stimulator Unit Output

The waveform of a rectangular, biphasic current pulse from the DSU was measured as the voltage drop across a constant load (**Figure 6**). The test found that the resolution of current amplitude modulation was 0.097 mA and the maximal current output was 50 mA. In the initial test, there was a discrepancy between the input pulse width and the measured output pulse width from the DSU. This difference remained fairly constant within the full range of pulse width modulation and was estimated at about 3.2 μ s, on average (**Figure 6(b)**). This difference between input and output pulse widths was due to a delay in the hardware component. This discrepancy in output pulse width was then compensated with software correction in the DSU. The compensated pulse width was measured again as shown with green bars (**Figure 6(b)**).

**Figure 6.**

Relationship between input and output of H-bridge circuit measured before and after compensation for hardware bias in pulse width. **(a)** Full range of input and output relation of distributed stimulator unit. **(b)** Output of H-bridge circuit with constant error at 3.2 μ s before compensation. Error is reduced to <1 μ s after compensation.

The compensated DSU output showed a linear relation with input pulse widths ranging from 10 to 1,000 μ s (**Figure 6(b)**).

Communication of Multichannel Stimulation Profiles

Figure 7 illustrates the programmed stimulus profiles specified in the GUI and the profiles of DSU outputs. In this case, four channels of stimulation currents were preprogrammed and each channel had a different pattern of stimulation profile. The first channel of stimulation was set to increase linearly from 0 to 20 mA

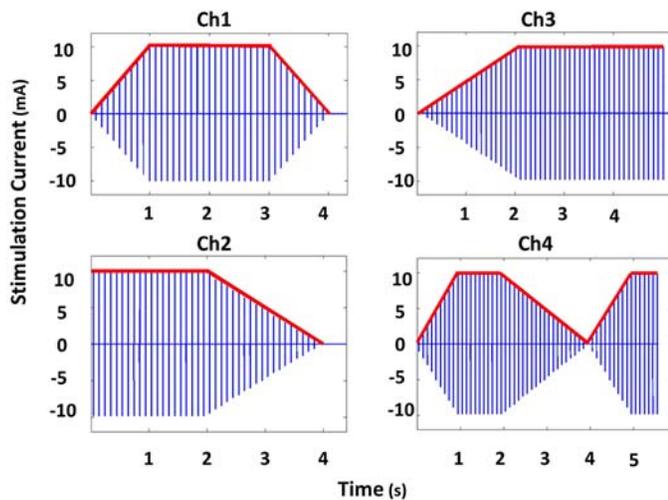


Figure 7. Multichannel stimulation profiles (Ch1–Ch4) prescribed in graphical user interface (red lines) and outputs of multichannel neuromuscular electrical stimulation (blue lines), which fit prescribed simulation profiles exactly.

between 0 and 1 s, maintain constant at 20 mA for 2 s, and decrease linearly from 20 to 0 mA. The second channel was set at 20 mA at the beginning for 2 s and to decrease linearly from 20 to 0 mA. The third channel was set opposite to that of the second channel. The fourth channel had a more complex profile. Tests showed that the DSU output profiles in blue lines matched the envelopes of specified profiles in red lines exactly in **Figure 7**, and the amplitude of biphasic pulse train of each DSU output was modulated according to the specified temporal pattern. This verified that the network system was able to faithfully transmit prescribed multichannel stimulation profiles to DSU stimulators.

Nondisabled Subjects Experiment

Tests in nondisabled subjects were performed to demonstrate the system's ability to elicit multijoint movements with synergistic stimulation of a set of muscles. **Table 2** summarizes the parameter values of threshold and uncomfortable stimulation states in three subjects. It is clear that the threshold parameters differed from subject to subject and from muscle to muscle. Thus, it is necessary to identify these parameters in each muscle for each subject before programming stimulation patterns.

Figure 8 shows the discrete multijoint movements elicited with multimuscle stimulation in three subjects. Two movements with properly programmed patterns of multi-

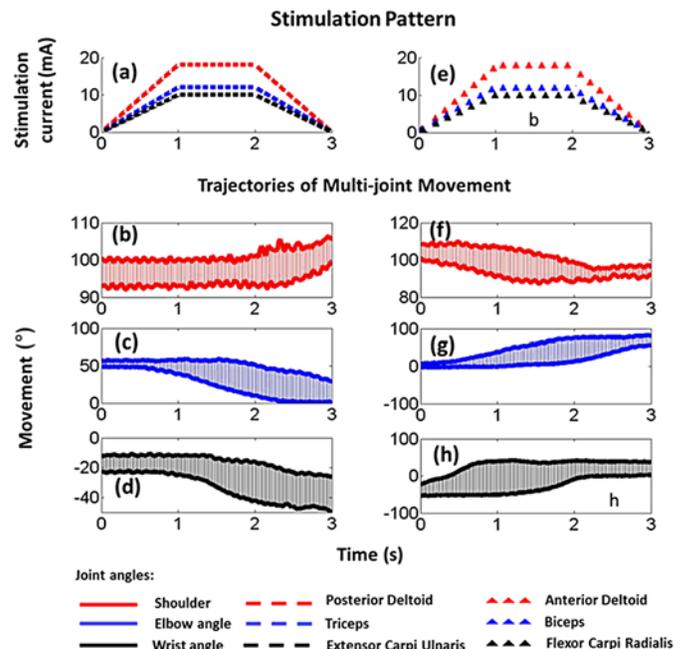


Figure 8. Results that demonstrate ability of neuromuscular electrical stimulation system to produce multijoint movement in nondisabled subject A. Multijoint movement is elicited by stimulating six muscles of arm. **(a–d)** Multijoint extension movement. **(e–h)** Multijoint flexion movements. Trajectory areas represent upper and lower limits of all repeated movements of shoulder (red), elbow (blue), and wrist (black) in extension and flexion. Stimulation pulse frequency is set at 25 Hz and stimulation pulse width at 100 μ s. Amplitude of stimulation current is modulated according to prescribed stimulation pattern in plots **(a)** and **(e)**. **Table 4** lists angle excursions of all three nondisabled subjects in multijoint extension and flexion movements.

sets of stimulation were performed, one for stimulation of flexors (**Figure 8(a)**) and the other for extensors (**Figure 8(e)**). Each stimulation set was repeated seven times in each subject. Movement trajectories of shoulder, elbow, and wrist joints were presented for flexion movements (**Figure 8(b–d)**) and extension movements (**Figure 8(f–h)**). **Table 4** presents and calculates a mean range of movements for each joint. In general, the angular excursion obtained in the shoulder joint was the smallest and the angular excursion in the elbow joint was the largest among the three joints. Test results in nondisabled subjects, nevertheless, demonstrated that the prototype network-based NMES system was safe to use in human subjects and can produce discrete multijoint muscle stimulation.

Table 4.

Angular excursions (in degrees) in multijoint movements in nondisabled subjects.

Joint	Subject A		Subject B		Subject C	
	Extension	Flexion	Extension	Flexion	Extension	Flexion
Shoulder	5.3 ± 2.1	11.2 ± 3.7	6.1 ± 1.7	6.1 ± 2.1	4.5 ± 1.5	4.2 ± 2.2
Elbow	40.2 ± 10.4	68.9 ± 15.1	47.6 ± 12.1	86.6 ± 20.2	58.4 ± 5.1	86.9 ± 8.2
Wrist	25.2 ± 7.1	25.4 ± 4.2	12.5 ± 4.3	9.9 ± 3.1	12.3 ± 4.1	23.2 ± 4.2

Subjects with Stroke Experiment

Table 5 summarizes the results of voluntary movements and NMES movements in four subjects with stroke. In this test, four variables were used to qualify the voluntary movements and NMES movements. The hand movement range indicated the ability of a subject to move the upper limb. The elbow and shoulder angles characterized the subject's ability to move individual joints. Acromion excursion was also used to evaluate trunk compensatory rotation made by subjects with stroke to accomplish the task.

Figure 9 contrasts the two types of movements performed by stroke subject A. In voluntary movement in column A, the hand movement followed a straight path limited to a narrow frontal part of the workspace (**Figure 9(a)**) and the hand velocity profile appeared to have multiple peaks (**Figure 9(b)**). The wrist joint was flexed (dropped) during voluntary arm movement (**Figure 9(c)**). The range of elbow extension was very small with almost flat velocity (**Figure 9(d-e)**). However, shoulder movement was more normal with multi-peaked velocity (**Figure 9(f-g)**). The average acromion excursion was 5.4 cm (**Figure 9(a)**), indicating that this subject used substantial trunk rotation to compensate for elbow extension. **Table 5** shows that all subjects with stroke used trunk compensation rotation to aid the arm extension task. Acromion excursion was from 1.2 cm in stroke subject B to 12.3 cm in stroke subject C.

Figure 9 illustrates the NMES-elicited multijoint arm extension movement in stroke subject A in column B. The hand trajectories were close to a straight line with a wider

range extending across the front line of the shoulder joint (**Figure 9(a)**). The hand velocity profiles tended to have a large single-peak followed by a small peak, closer to that of normal movement (**Figure 9(b)**). The wrist joint was extended during the arm movement due to concurrent stimulation of the extensor carpi ulnaris (**Figure 9(c)**). Elbow angle range was increased significantly with a single peak velocity (**Figure 9(d-e)**). The shoulder joint moved synchronously with the elbow joint with a large initial velocity peak followed by a small velocity peak (**Figure 9(f-g)**). With NMES, stroke patient A used less acromion movement to aid arm extension. The acromion excursion in stroke subject A was reduced from 5.4 to 1.3 cm (**Table 5**). Compared with voluntary movements, NMES movements demonstrated a more normal pattern and improved quality of multijoint arm movements.

DISCUSSION

We have designed, developed, and tested a distributed NMES system that is capable of multichannel muscle stimulation and flexible for expansion in future clinical applications. Compared with a simple multichannel stimulator, we favor distributed architecture over centralized architecture for several reasons: (1) a distributed design does not require synchronization across various components of the overall system, which has been proven highly inefficient when the system scales; (2) due to the high scalability enabled by our distributed design, additional DSUs

Table 5.

Evaluation variables of multijoint arm movement in subjects with stroke.

Variable	Subject A		Subject B		Subject C		Subject D	
	VOL	NMES	VOL	NMES	VOL	NMES	VOL	NMES
Acromion Excursion (m)	0.054 ± 0.031	0.013 ± 0.003	0.012 ± 0.009	0.006 ± 0.002	0.123 ± 0.015	0.076 ± 0.0145	0.013 ± 0.008	0.019 ± 0.010
Hand Movement (m)	0.316 ± 0.122	0.435 ± 0.036	0.389 ± 0.077	0.427 ± 0.024	0.647 ± 0.090	0.748 ± 0.060	0.664 ± 0.047	0.347 ± 0.061
Elbow Angle (°)	7.0 ± 6.9	36.7 ± 8.1	15.4 ± 3.0	19.6 ± 3.8	37.0 ± 5.1	29.4 ± 3.7	45.7 ± 11.8	34.5 ± 3.5
Shoulder Angle (°)	23.5 ± 21.8	22.3 ± 7.3	48.1 ± 10.5	39.0 ± 4.1	0.6 ± 14.7	73.7 ± 7.0	1.0 ± 6.8	38.5 ± 7.5

NMES = movement elicited by neuromuscular electrical stimulation, VOL = voluntary movement.

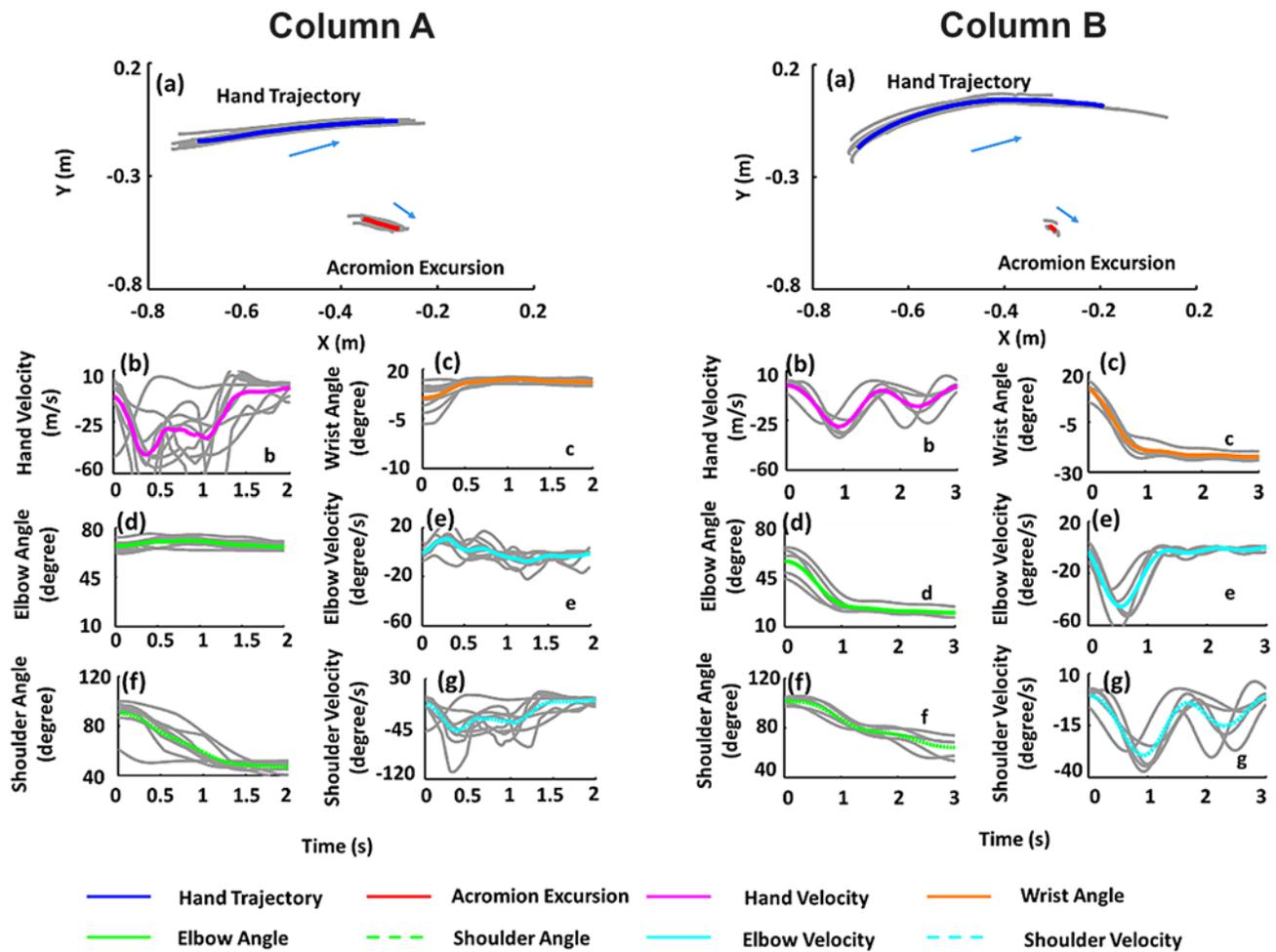


Figure 9.

Comparison of multijoint arm movements in stroke subject A. Column A illustrates voluntary arm movement by stroke subject A, and column B presents arm movement of same subject produced by neuromuscular electrical stimulation. Results include (a) hand movement and acromion excursion, (b) hand velocity profile, (c) wrist movement, (d) elbow angle, (e) elbow velocity, (f) shoulder angle, and (g) shoulder velocity. Hand trajectory shows ability of subject to perform task. Acromion excursion, elbow angle, and shoulder angle describe quality of movement at joint level.

can be added to the backbone system without significantly losing performance; and (3) a distributed system is generally less susceptible to component failures since DSUs do not propagate their errors to the rest of the system, and this feature is innate to distributed systems compared with centralized systems.

Nondisabled subject tests indicate that the system is safe and functional in producing multijoint movements with synergistic stimulation of a set of upper-limb muscles. In these tests, no adverse reactions from subjects were observed with stimulation parameters set within the limits (Table 2). The GUI is designed for therapists or technical

aids to program a subject-specific pattern of stimulation with a set of muscles. The distributed system architecture is also amenable to extension of functionality, e.g., in combined use with motion and EMG sensors as well as robotics. The ongoing work in system development is to mitigate the size of the DSU by application-specific integrated circuit technology [57]. The new DSU chip design will allow the network-based NMES system to be wearable in patients at home. The DC-DC voltage booster developed here will be useful in providing the necessary voltage supply for the stimulator from a normal battery in a wearable system.

The distributed NMES system developed in this study may provide an innovative solution for rehabilitation training of patients with stroke because it allows multichannel stimulation of a synergistic set of muscles. The system has the flexibility to allow personalized programming of muscles and temporal patterns of stimulation. The device can be deployed to home use for continued rehabilitation for outpatients with stroke. In addition, the distributed NMES system can be combined with robotic technologies to develop a hybrid therapy for subjects with stroke [4–7]. Clinical trials of an upper-limb robotic system demonstrated its effectiveness in a large patient population [8,58]. An emerging therapy based on multimuscle NMES may have clinical values that have not been provided with current NMES devices and clinical methodologies of interventions.

The pilot tests in nondisabled subjects and subjects with stroke demonstrated the feasibility of our system. In the experiment, we established a procedure to place electrodes to the motor point of muscles and to program a stimulation pattern to assist subjects with stroke in performing multijoint arm extension movements. Experiment tests showed that the distributed NMES system is safe if proper limits of stimulation parameters are measured and set for each subject (**Table 2**). Results in both nondisabled subjects and subjects with stroke indicate that it is feasible to produce multijoint arm movements with relatively simple patterns of multimuscle stimulation (**Figures 8–9**). However, there are significant differences in the residual motor ability among subjects with stroke (**Table 5**). Stroke subjects A and B showed weak voluntary control of the elbow joint, and stroke subjects C and D revealed weak voluntary movement in the shoulder joint. All subjects used substantial trunk rotation, as indicated by acromion excursion, to compensate hand movement for the task. This indicates that compensatory action is directed at task level, not at joint level. It appears that multimuscle NMES may expand the range of motion of joints that have weak voluntary control. If NMES is used to assist the voluntary control of patients, the combined effects will further improve motor task performance. In future clinical study, the assistive mode of NMES should be developed for rehabilitation training in patients with stroke.

How to design an optimal strategy of multimuscle stimulation to achieve task-oriented training is one of the central issues in NMES rehabilitation for stroke [2]. Whether a more natural method of muscle stimulation

can improve the effectiveness of stroke rehabilitation is still an open question. Recent advances in neurophysiology of motor control revealed that muscle synergies are likely programmed in the planning and control of movement by the central nervous system [59–61]. Muscle synergies may provide a solution to the degrees of freedom problem in motor control by using a much smaller number of variables in some fixed combinations to produce a larger repertory of behaviors. It has been shown that muscle synergies can also explain how to accomplish a movement at task level by identifying the relevant muscle group [62–63]. The nature of muscle synergy in task planning and execution may help to elucidate the question of how to activate a group of relevant muscles to best achieve stroke rehabilitation. The network-based NMES system developed in this study allows synergistic stimulation of multiple muscles to perform task-oriented training. However, the synergistic pattern must be adjusted to assist individual subjects with stroke complementary to their voluntary residual motor ability. The control algorithm may then adaptively adjust stimulation patterns and parameters according to changes of voluntary motor control of the subject with stroke over the course of rehabilitation training.

CONCLUSIONS

In this article, a prototype network-based NMES system employing surface stimulation technology has been described and tested for clinical rehabilitation in patients poststroke. Results of laboratory tests indicate that system performance meets design specifications and that the system is safe to use in human subjects. Results of nondisabled subject tests also show that stimulation profiles of multiple muscles can be programmed to achieve multijoint movements. Further experiments in subjects with stroke show that the distributed NMES system can improve task-oriented performance with expanded hand and joint movements and reduced trunk compensatory rotation. The NMES system provides an innovative solution as an emerging therapy for motor function recovery in patients with stroke in the hospital and at home. Future work is to complete integrated circuit implementation based on the prototype for a wearable network-based NMES system and to conduct more extensive trials to evaluate the clinical effectiveness.

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Analysis of data: X. He.

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