LETTER TO THE EDITOR

A Human Interactive Hybrid FES-Robotic System Applicable to Improvement of Foot Drop after Stroke: Case Report of a Patient with Chronic Stroke

Dear Editor

Utilizing the intelligent robots and functional electrical stimulation (FES) for motion recovery, not only after therapeutic surgery but also after suffering a neurological disorder, has attracted researchers' interests, as, the aforementioned devices can pave the way for conducting the top-down rehabilitation approaches (1). According to the top-down approach, rehabilitation is driven by neural plasticity (1). The essential element of the top-down approach is active participation. In fact, such rehabilitation approaches involve the neural system (top), through active participation, to influence the distal physical level (bottom). In addition, rehabilitation using robotic technology can be intensive, repetitive, and task oriented (2, 3). During the recent years, many researchers have tested the effectiveness of gait training with robotic exoskeleton on clinical outcomes in patients with stroke (4-7). The ability of the wearable exoskeleton systems for longitudinal overground training of walking in hemiparetic patients after stroke has been shown (4-7). Along with the robotic devices, some evidences prove that FES can be a useful methodology in motor recovery after stroke (8). Faster rehabilitation process in hemiplegic gait utilizing the FES combined with other gait training approaches has been reported, but should yet be more assessed (9, 10). Nevertheless, no intriguing evidences have been reported specifically with respect to improving the walking in patients with foot drop due to over ground gait training using the hybrid FES-robotic rehabilitation systems. Therefore, in this case study, we focused on gait improvement of a patient with chronic post stroke right foot drop using a hybrid FES-robotic system

Human-robot interactions can pave the way for eliciting the top-down motor learning because such processes stress active patient involvement has been adopted. In fact, a stroke patient received gait training using the provided human-interactive hybrid FES-robotic system. Accordingly, the aim of this case study was to assess the efficacy of the gait exercise utilizing a human-interactive rehabilitation system. In fact, the effectiveness of the applied gait training on functional performance of a stroke patient was evaluated for this goal. The study subject was a 30-year-old man who was afflicted by hemorrhagic stroke 8 years ago. According to the guidelines endorsed by the american Stroke Association, he was a chronic phase stroke case (11). His right side was affected, and he had gotten all ordered physical therapies. He had suffered from right foot drop and loss of dexterous grasping capability of the right hand. He could voluntarily control all leg joints except the right ankle joint. His foot drop had led to deficit gait. He had to spend considerable energy during each gait cycle to preserve his balance due to improper coordination between the left (unaffected) and right affected ankle joint.

The implemented FES-robotic system has two separate parts including the electrical stimulator and active mechanical orthosis. Orthosis: a direct-current (DC) motor along with a wearable component accounted for active mechanical orthosis. During the swing phase of the gait, dorsiflexion and plantarflexion of the ankle are performed consecutively. During the ankle dorsiflexion, the total torques arising from the stimulation of the ankle dorsiflexor muscle and the DC motor causes the ankle joint to rotate inward. While, during the ankle plantarflexion, the generated torque by the DC motor is enough to cause the ankle joint to rotate downward. Since the muscles have time varying properties, a closed loop control strategy was utilized for online adjustment of the stimulation pulse width of the ankle dorsiflexor muscle. Symmetric rectangular biphasic pulses were delivered to the tibialis anterior as a dorsiflexor muscle. The electrical pulse width could be adjusted between 0 to 1 ms (resolution: 1µs), and the pulse amplitude could be adjusted between 0 to 80 mA (resolution: 1 mA). The frequency of the stimulation pulses was 25 Hz.

In this study, an interaction strategy was applied to let the patient manually determine the onset of dosiflexion and plantarflexion of the affected ankle joint. A piezoelectric sensor was inserted on a plate, and the

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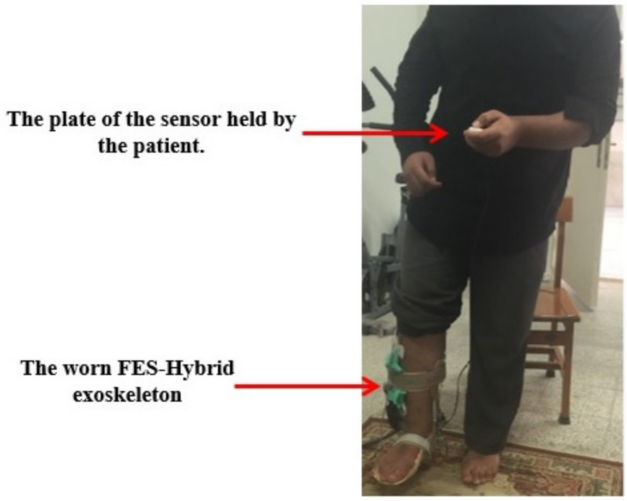

Figure 1. The patient held a plate in the unaffected hand, while a piezoelectric sensor was located on that plate. He touched the sensor to start the ankle dorsiflexion and the ankle plantarflexion at the start of the swing phase and the stance phase, respectively.

patient held the plate in his unaffected hand (left). He was instructed to touch the sensor twice during each gait cycle. He once touched the sensor to start the ankle dorsiflexion (at the beginning of the swing phase), and once again to start the ankle plantarflexion (at the beginning of the stance phase). In fact, the patient consciously determined the onset of dosiflexion and plantarflexion. In this manner, a cognitive sub-process has been incorporated in the movement training process. It was expected that such a cognitive process can enhance and expedite the motor re-learning process. Figure 1 shows how the patient held the plate in his unaffected hand and Figure 2 shows different parts of the system. Also, it demonstrates how the patient wore it on the affected ankle. The applied torque about the ankle joint was produced using an active motor (through applying an external force) alongside a FES system (through eliciting the muscle force due to electrical muscle stimulation). The ankle joint is dorsiflexed around the line passing through the medial and lateral malleoli [Figure 2]. The patient received 16 sessions of exercise therapy using the hybrid FES-robotic system during four months. He took between 20 to 50 consecutive steps during each session while wearing the robotic system on his affected ankle joint.

Figure 2. Different parts of the provided hybrid FES-robotic system worn on the affected leg of the patient.

In this study, three clinical tests including functional ambulation category (FAC), Fugl Meyer Assessment Lower Extremity (FMA-LE), and mini balance evaluation system test (Mini-BESTest) were conducted to evaluate the status of the functional performance (12-14). Table 1 shows the values of the clinical indexes associated with three clinical tests. The indexes determined once before performing the exercise therapy and once after performing the exercise therapy. It is ample clear that all quantitative clinical indexes have been increased after the patient received the exercise therapy. The minimal detectable change (MDC) of the FMA-LE is 4 (15). According to the Table 1, the sensory and motor scores of FMA-LE increased 3 and 7 points, respectively. Therefore, improving the motor functioning can be certified while improving the sensory functioning cannot be acceptable. However, relative increment of sensory score along with the acceptable increment of motor score can be interpreted as improving the sensory-motor coordination during walking. In addition, the Mini-BES score increased 5 points. Since the MDC of the Mini-BES is 3, a 5-point increase can be construed as improving the proprioception which led

Table 1. The values of the clinical indexes associated with three clinical tests. The indexes determined once before and once after performing the exercise therapy.

	FAC (0-5)	FMA-LE Motor score (0-12)	FMA-LE Sensory score (0-34)	Mini-BES (0-28)
Before gait training	3	23	8	19
After gait training	4	30	11	24

to better balance performance. Also, the FAC score hit 4 (16). Since the maximum value of this score is 5, such increment can also show the patient's relatively better ambulation status. These results imply improving the sensory-motor coordination that can be attributed to performing a motor re-learning process. Also, these outcomes show the intriguing influence of the designed exercise therapy using the hybrid neuroprosthesis on improving the sensorimotor and balance function. Overall, it can be concluded that involving the patient for determining the onset and offset of the movement can be an efficient strategy for design of patient-robot interaction process. In addition, the outcomes prove the efficacy of using FES along with the active mechanical orthosis in ankle motion recovery. Thus, though we carried out a case study, this work might open a new frontier for involved researchers.

Due to some limitations we carried out a case study. For conducting the study with more human cases, the size of the wearable part of the system has to be adjustable for different patients. In addition, the human-robot interaction process has to be modified and user friendly because even the stroke patients with cognitive deficiencies can use it easily. Solving these limitations needs more effort, cost, and time. However, it can be concluded that exercise therapy using the human interactive FES-robotic system can improve the gait quality in a chronic stroke patient.

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