A Hybrid Control Strategy for Tendon-actuated Robotic Glove and Functional Electrical Stimulation – A Preliminary Study

Antonio Ribas Neto[1,2], Julio Fajardo[1,3], Victor Ferman[1], Eric Fujiwara[4] and Eric Rohmer[1]

***Abstract*— People who suffered a stroke, or spinal cord injury, still rely on the use of exhaustive physical therapy for recovery. When the aftereffects of these illness act on upper limbs as the hand, this causes a great impact on their quality of life. As alternative resources to the physical therapy, functional electrical stimulation and exoskeletons, or wearable robotic gloves, are consolidating as important resources to help to address this problem. Functional electrical stimulation has been proved to be an efficient rehabilitative technology, while exoskeletons are assistive technology helping people with a deficiency in their daily activities. In order to put these technologies working together, we propose a hybrid control strategy, making use of a tendon-driven robotic glove and functional electrical stimulation. Our aim is develop a glove-like orthosis for hand with the advantages of both technologies. This combined control strategy may have the potential to be used for hand rehabilitation.**

I. Introduction

Most people who suffer a stroke, or a spinal cord injury (SCI), and who survive, are temporarily or permanently debilitated. For these people, conventional exercise therapy was, and until now, is the mainstay of recovery and rehabilitation. Development of clinical neuroscience, electronic engineering, and robotics, started to play an important role in the lives of these people. Researches in neuroscience, involving neuroplasticity, are helping to understand how the complex motor system works, and scientific investigations focused on devices and strategies are gradually providing the knowledge to better tackle the problem of restoring body movement and improve outcomes.

In the last two decades, promoted by advances in robotics, an increasing number of hand exoskeletons, or wearable soft robotics [1], arouse as a promise to boost therapy and, at least, assist people with disability to perform their activities of daily living (ADLs). Developed exoskeletons as [2]–[4] appear to be well-suitable for this purpose. Although exoskeletons are important in hand rehabilitation because they offer the support to stabilize the joints, they do not prevent muscle atrophy if the patient provides no force themselves [5].

Alongside the use of exoskeletons, is functional electrical stimulation (FES). Benefited from electronic engineering advancements, FES is other leading support applied to rehabilitation. Since the first uses as hand rehabilitation technologies, as in [6]–[8], the application of FES has been gaining prominence as an intervention to improve outcomes, meanly when used along therapy [9,10]. Moreover, despite several drawbacks as it may being painful for the patient, difficult to achieve precise and repeatable movement [11], FES brings direct results as reducing muscle spasm, increasing range of motion, and retarding disuse atrophy [9,12,13].

Nevertheless, there appears to exist a wide gap between the use of exoskeleton - generally considered as an assistive technology - and FES - a rehabilitative technology - on the same device. As pointed out by [5], amongst the few robotic devices available for rehabilitation, most are not suitable for home-rehabilitation because they are bulky, expensive and lacks of portability. Furthermore, there are few commercial devices using or proving FES intended to deal with the complicated operations such as hand movements [11,14].

Taking this into account, we will propose a hybrid control strategy using an exoskeleton and FES, aiming to develop a portable device to be used to perform ADLs, at first improving joint range of wrist motion, and later with continuous research, achieve the ability to open and close the hand. In addition, since we will use a wearable robotic glove/exoskeleton and FES to provide forces, our devices has the potential to work as an assist-as-need tool. Other advantages of the proposed hydrid control strategy, will be the reducing of magnitude of the pain at the electrode sites and delaying muscle fatigue, since that the use of FES do not need to be as intense to cause the same movement when using only FES, due to the supporting force coming from the exoskeleton.

Additionally, we also intend to make use of an open-source hardware/software stimulator comprised by a shield and an Arduino, since there is a considerable number of electrical stimulator, but they are proprietary software/hardware. Thus we can provide a low-cost portable device with the advantages of both assistive and rehabilitative technologies.

In order to present this the hybrid strategy, this paper is divided in five sections. This section presented some issues related with the use of exoskeletons and FES, and exposed the necessity of having hybrid exoskeletons for the upper limbs rehabilitation. It was also introduced our researching purpose. In section II, the hybrid control strategy is explained

This work was supported by FAPESP Grant 2017/25666-2, and MCTI/SECIS/FINEP/FNDCT Grant 0266/15.

[1] Authors are with Department of Computer Engineering and Industrial Automation, School of Electrical and Computer Engineering, University of Campinas, 13083-852 Campinas, SP, Brazil.

[2] Author is with Federal Institute of Education, Science and Technology Catarinense, 89609-000 Luzerna, SC, Brazil. PhD Candidate. antonio.ribas@ifc.edu.br

[3] Author is with Turing Research Laboratory, FISICC, Universidad Galileo, Guatemala City, Guatemala. PhD Student. werjevfh@galileo.edu

[4] Author is with Laboratory of Photonic Materials and Devices, School of Mechanical Engineering, University of Campinas, 13080-860 Campinas, SP, Brazil. fujiwara@fem.unicamp.br

in details, followed by section III regarding the methods and materials used to conduct the experiments. The result and discussions of preliminary experiments to validate the hybrid control strategy are reported on section IV, conclusion and future works are considered on section V.

II. Hybrid Control Strategy Proposal

It is well known that the extended use of FES has limitations due to muscle fatigue. This occurs because FES induces an unnatural motor unit recruitment order [13]. To try to cope with this drawback and widen the using time of FES without muscle fatigue, in what follows is proposed a hybrid control strategy for the tendon-driven orthosis.

To understand the methodology, consider the Fig. 1 (a) that contains a generic waveform of FES, with ramp up and ramp down time, and a period of time window, between t_1 and t_2, which the stimulation is kept constant by using FES. The ramp up time is a transient phase used to progressively excite the muscle, that is, changing the rate at which the current achieves the maximal amplitude, imitating how muscles are normally recruited for function. In addition, using the ramp up will make the procedure more comfortable for the user. The ramp down period is also a transient phase in which occurs the gradual fall of stimulation intensity, mimicking relaxation of voluntary contraction. The plane current wave between the time span t_1 and t_2 is the extended period of stimulation which is responsible the most for muscle fatigue. By reducing the stimulation time the muscle fatigue is reduced. For example, consider a user suffering from hand disability, unable to close their hand. The user is stimulated only by FES for closing his hand, and keeps objects grasped between the time span t_1 and t_2. During this time interval, the hand is sustained closed purely by stimulation of the muscles responsible for closing the hand. If the time window between t_1 and t_2 is long, then the muscles of the user's hand will become fatigued sooner.

Now, consider Fig. 1 (b) also has ramp up and ramp down time, but it has a plane waveform differently from Fig. 1 (a). In the time window between t_1 and t_2 it is possible to have a period of time sustained by FES and/plus tendon-driven orthosis. Consider the same user from previous example, maintaining grasped the same object only using FES. Whether FES is turned off, it is probable that such object will fall. However, whether the user is using an orthosis with tendon-driven actuator, in this time window, the orthosis can provide the necessary force to maintain the hand firmly closed even without FES. Additionally, in this case it would be possible to add FES between t_1 and t_2, if wanted, as can be seen in Fig. 1 (b).

The rationale for using this procedure in the stimulation of the hand muscles is to try to minimize the time the muscles remain under stimulation, and consequently reduce muscles fatigue. The current state-of-the art in this field is not showing any similar to this hybrid FES/tendon approach.

In the experiments described on the next sections, it will be employed FES only in the period of time related to ramp up, with the purpose of starting the contraction of closing

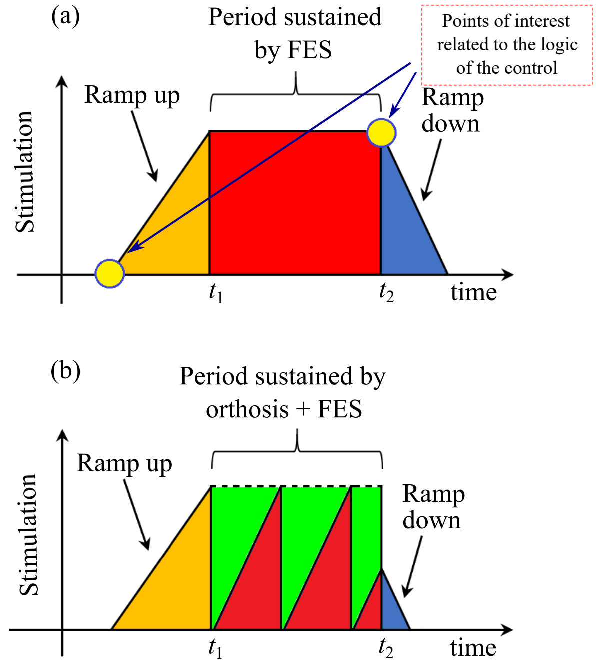

Fig. 1. (a) Generic waveform of FES, and (b) the new proposed waveform for FES and/plus tendon-driven orthosis.

the hand. Afterwards to maintain the closed hand posture, the tendon-driven system will provide the necessary force to keep the object grasped.

A. Logic of the Hybrid Control Strategy

In order to put into action the hybrid control strategy, Fig. 2 contains a self-explanatory block diagram with the logic of the control. A more detailed description on the control logic can be found in [15], except for the logic associated with the triggering of the FES.

Fig. 1 is related with Fig. 2 as follows: when detected the user's intention to close the hand (FMG Flexor RMS value greater then a FMG Flexor Threshold collected by an optical force myography (FMG) sensor placed on the flexor digitorum superficialis (FDS) muscle area), the actuating system responsible for closing the hand is turned on as well as the FES system. The FES system is activated and hand is kept closing until the signal coming from the force sensing resistor (FSR) glued on the index fingertip (see Fig. 4) surpasses a settled force setpoint. When it happens, it means that the glove touched a surface's objects, and both tendon actuating system and FES are switched off. The user's hand remains in this posture, with the object grasped, until a new intention of opening the hand is detected, which is detected by another FMG sensor placed on the extensor digitorum communis (EDC) muscle area. In conventional orthoses using only FES, the grasp is stood exclusively by the use of FES (see Fig. 1 (a)), the extended period of time which is responsible for provoking muscle fatigue.

When the FMG Extensor RMS value coming from the FMG placed on EDC muscle exceeds a FMG Extensor Threshold, the FES is turned on, the rotation of the motors is reversed, and hand starts to open. To simplify the control related to the opening of the hand, the hand remains opening and FES actuating, for the same time as glove was kept closing. This procedure ensures that the hand returns to its resting position, that is, with the hand opened. The same input control is used to switch the FES off. Thus, the glove is ready to perform another movement.

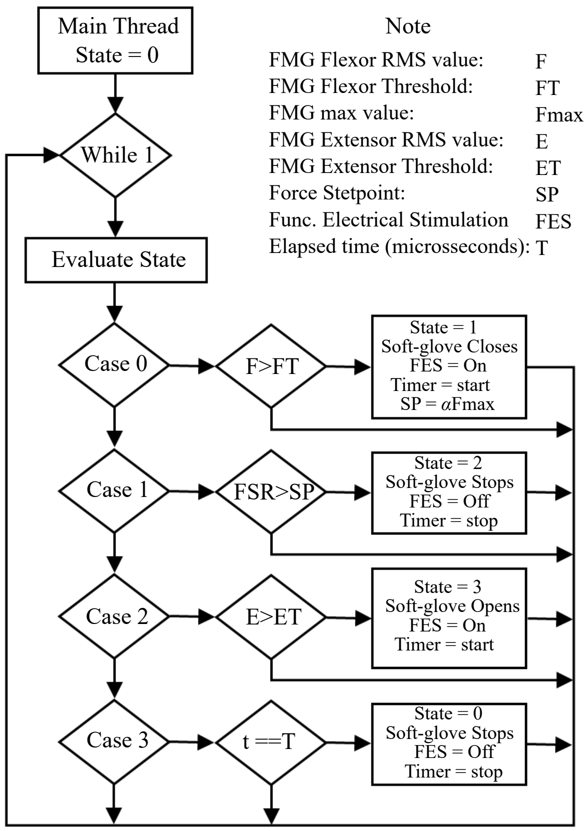

Fig. 2. Main loop flowchart of the hybrid control strategy.

Although the logic for the FES system actuation when the hand is opening has been also described, in the proof of concept involving the hybrid control strategy proposed here, only the FES system contributing to the hand closing will be used. Other consideration of the hybrid control strategy is the possibility of having FES actuating whereas the grasp is kept. Fig. 1 (b) has a possible suggestion of using the hybrid control strategy in cooperation with the glove's use.

As the surface electromyography (sEMG) can be influenced by the use of FES, a solution to deal with this matter is to apply an optical fiber FMG sensor. The construction of the sensor and how it operates is reported on [15].

III. Methods and Materials

In this work, we propose a hybrid control strategy making use of an exoskeleton (a tendon-driven glove developed as presented in [15]), and a FES system to reach the advantages of both methods. To implement the hybrid control strategy, we employ an Arduino Uno with a shield used for electrical stimulation, both open software/hardware. The shield is a stimulator device capable to generated biphasic wave form in two separated channels. The system also comprises two channels of a FMG transducer based on optical fiber to interpret the user intent. The signals collected by the sensors are processed by a microcontroller unit (MCU) that accommodates the logic of control hybrid strategy in order to run the operations of closing and opening the hand as well as to switch on/off the FES system. The MCU sends angular velocity commands to two Dynamixel AX-12A+ Smart Servos using a Daisy Chain topology and through a single wire Half-Duplex asynchronous serial communication. Each motor is linked with a 3D printed nonbackdrivable mechanism. A force-sensing resistor (FSR) glued on the index fingertip is used as grip strength feedback performed by the glove. The block diagram proposed in Fig. 3 represents an overview of the full system.

IV. Results and Discussion

All the experiments conducted regarding the proof of concept involving the hybrid control strategy proposed were developed with FMG sensors and active electrodes arrangements as represented in Fig. 4. A healthy male student volunteered for this study.

To provide electrical stimulation, a two-channel open-hardware electrical stimulator was used, the "STIMSHIELD" [16]. This stimulator is a shield built to be used with Arduino, and it is possible to achieve up to eight channels by cascade integration. Additionally, it is able to generate constant stimulation frequency of 40 Hz, and constant stimulation magnitude up to 80 V. Initial stimulation parameters were: symmetrical square biphasic pulses width; stimulation frequency equal 25 Hz; ramp up and ramp down time, 2 s and 2 s, respectively; pulse width 150 μs; sustained (maintenance pulse) depended on the experiment.

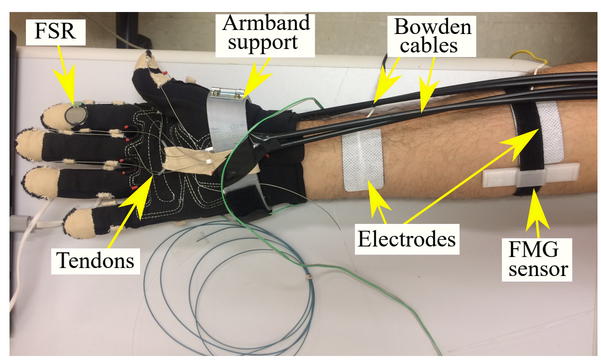

Fig. 4. FMG and electrodes arrangements on the forearm for sEMG recording on EDC muscle when FES is applied on FDS.

For the FES application, two active, rectangular self-adhering electrodes (Carci Trode, dimensions 3 x 5 cm), were placed over the motor point of the targeted muscle (as shown in Fig. 4). The electrode sites were cleansed with 70% isopropyl alcohol for removing skin fat, but not shaved.

The first experiment was carried out to evaluate the influence of FES on the sEMG and FMG measurements. It consisted in recording the sEMG signal on the EDC muscle

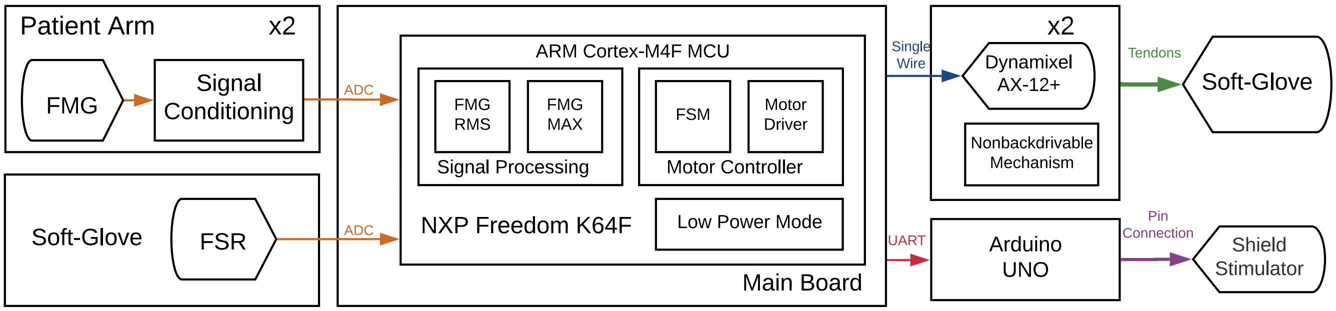

Fig. 3. Block diagram showing the system architecture of the hybrid controller and the wearable robotic glove.

side when applying FES on FDS muscle side. The sEMG signal was collected using the MyoWare muscle sensor with pre-gelled disposable electrodes (Kendall, shape/size round/24 mm diameter, thickness 1 mm), recorded with a sample rate of 1 kHz, and filtered using an IIR Elliptic Band-Pass filter of order 20 with a pass-band from 100 to 480 Hz and quantized for single precision. The filter was implemented using the Biquad Cascade IIR Filters Using a Direct Form II Transposed Structure from the CMSIS-DSP API for ARM Cortex-M4 microcontrollers [17]. Fig. 5 has the representation of the signal processed.

As can be seen in Fig. 5, part (a) represents the artifacts of a sEMG signal, whereas part (b) has the stimulation artifacts in the sampled sEMG signals. This latter recorded sEMG signal consists of the so-called M-waves, which represent the level of muscle excitation caused by FES. It is clear from the results that sEMG cannot be used without an auxiliary procedure of suppression of artifacts when recording sEMG signals using FES. On other hand, this reinforces our choice by the use of FMG sensors, which are not susceptible to electromagnetic noise.

The second trial consisted of two tasks to appraise the hybrid control strategy. The first task was to grasp a stick glue, and the second, to grasp an insulating tape, as represented in Fig. 6.

The explanation of the Fig. 6 is based on the main loop representation portrayed in Fig. 2. As can be noted in Fig. 6 (a), until approximately 1.8 s the system is in *State 0*, which indicates the motors are stopped and the FES system turned off, and the hand is opened. When the FMG sensor placed on the FDS muscle detects the flexion movement intention, the state changes to *State 1*, the motors and the FES systems are turned on, and glove starts closing. The dashed line represents the *On* and *Off* states of the motors and the FES, where 0 V represents the *Off* state of the motors and FES system. Notice that the hand is kept closing until the FSR signal surpasses a threshold and them switches to *State 2*. It implies the FSR touched the surface's object and the motors and the FES are switched off. When the extension movement intention is detected by the FMG sensor placed on the EDC muscle, the state changes to *State 3*, motors' rotations are reversed and glove starts opening. As established before, we are using the FES system only for closing the hand. *State 3* remains by the same time that glove stood closing, i. e. by

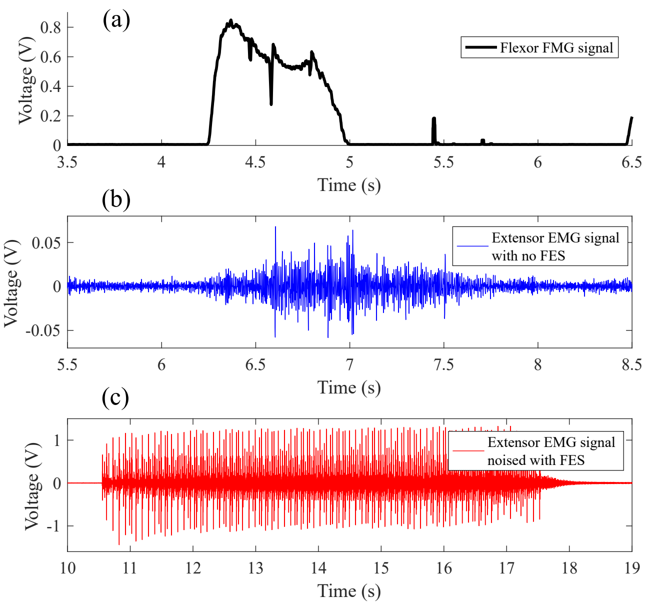

Fig. 5. Representation of the sEMG recorded on EDC muscle when FES is applied on FDS: (a) FMG signal; (b) sEMG artifacts recorded without the influence of FES; (c) M-waves containing the influence of the FES.

the same time that *State 1* remains in high level, and thus switches again to *State 0*, when motors are turned off. It means that glove is fully opened again and both motors and FES are turnef off. Thus, the system continues in this state until a new flexion movement intention is detected, restarting the loop.

The main differential taking into account an orthosis that uses only FES is the time window between states 1 and 2. In the *State 2*, the FES system is turned off and the force necessary to sustain the object is provided by the tendon-driven glove. This is possible because the glove uses a nonbackdrivable mechanism to keep the hand posture. Thus, in this period of time, we can reduce the use of FES, and consequently the muscle fatigue.

The task regarding the insulating test, has results similar to the task considering the stick glue task. As can be seen in Fig. 6 (b), the main difference remains on the contribution of the use of the differential mechanism, i.e. the fingers adaptation to the surface's object, which can be seen approximately in the time of 5 s. Notice that the FSR signal begins to increase

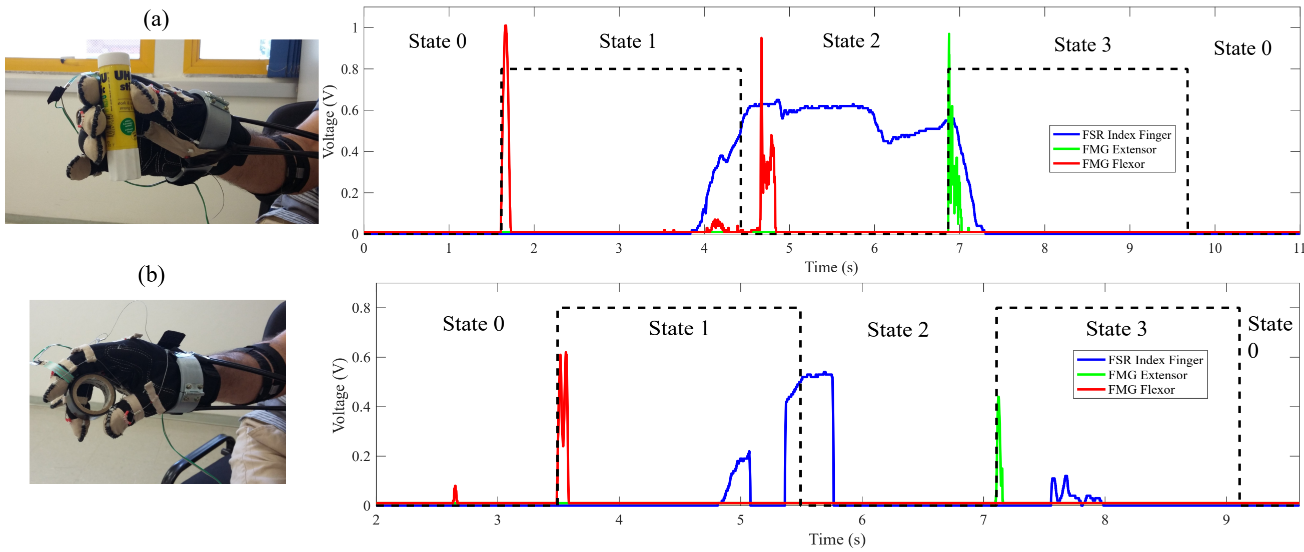

Fig. 6. Sensor responses and states for the tasks of (a) grasping a stick glue and (b) an insulating tape.

when index finger touches the object. However, thanks to the differential mechanism, the force exerted by the tendons causes the middle finger to begin to flex, until it reaches a point where the forces are in equilibrium and the FSR restores contact with the tape until the FSR threshold be reached.

Note that in both states 2 represented in Fig. 6, the FMG Flexor and FSR Index Finger signals are significantly different. In Fig. 6 (a), the FMG Flexor signal presents a spike, and in Fig. 6 (b) it does not appear. Since it is being used FES, the muscle volume can be changed by FES and generated such a peak. As for the FSR Index Finger signal, from Fig. 6 (a) it is clear that the sensor maintains contact with object's surface during all the time the object is kept grasped. The same does not happen when grasping the stick glue, as can be deduced from Fig. 6 (b).

Additionally, in both tests, when conducting the experiments, it was notice that when FES system is turned on, the hand suffer a slight sudden movement. It was related to the ramp up time chosen, and can be managed by changing its value.

V. Conclusions and Future Works

In this paper we proposed a preliminary study related to the development of a hybrid control strategy using an exoskeleton and a FES system, capable of improving joint range of wrist motion and with the potential to reduce muscle fatigue. In this first moment, the hybrid exoskeleton prototype using FES has the potential to be used as an assist-as-need device. In order to afford effective home-based rehabilitation and assist people with disability perform their ADLs, we need to focus on software and hardware development to furnish an improved embedded solution.

A consideration about the device is that it cannot solve the problem of muscle hand selectiveness, i.e. it cannot control the 5 fingers separately. To do that, a stimulator with more channels are necessary as well as guide each finger separated by replicating the tendon-driven mechanism for each finger.

As regarding the use of the FMG sensor, depending on the amount of residual muscle activity, it may be not suitable for all people with severe hand disability. In this case, other approach more sensitive to the lacking of muscle activity needs to be applied in conjunction with a way of suppressing the artifacts containing stimulus electrically evoked by FES [18].

Another two important future works are change the passive actuation to an active actuation, and implement a shared control strategy to dose the contribution of the glove and FES on hand's force, and create a protocol to evaluate muscle fatigue using the exoskeleton and FES.

Acknowledgement

The authors would like to thanks the Prof. Maria C. F. de Castro for lending us the stimulator, and the students Willian H. A. Silva and Matheus K. Gomes for developing and implementing the algorithms involving the optical FMG sensor.

References

[1] T. Shahid, D. Gouwanda, S. Nurzaman *et al.*, "Moving toward soft robotics: A decade review of the design of hand exoskeletons," *Biomimetics*, vol. 3, no. 3, p. 17, 2018.

[2] M. A. Delph II, S. A. Fischer, P. W. Gauthier, C. H. M. Luna, E. A. Clancy., and G. S. Fischer, "A soft robotic exomusculature glove with integrated sEMG sensing for hand rehabilitation," *2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*, pp. 1–7, 2013.

[3] P. Polygerinos, Z. Wang, K. C. Gallowaya, R. J. Wooda, and C. J. Walsha, "Soft robotic glove for combined assistance and at-home rehabilitation," *Robotics and Autonomous Systems*, vol. 73, p. 135–143, 2015.

[4] B. B. Kang, H. Lee, H. In, U. Jeong, J. Chung, and K.-J. Cho, "Development of a polymer-based tendon-driven wearable robotic hand," *IEEE International Conference on Robotics and Automation (ICRA)*, vol. 22, no. 1, pp. 97–105, 2015.

[5] A. M. Stewart, C. G. Pretty, M. Adams, and X. Chen, "Review of upper limb hybrid exoskeletons," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 15 169–15 178, 2017.

[6] M. J. IJzerman, T. S. Stoffers, F. A. C. G. in 't Groen, M. A. P. Klatte, G. J. Snoek, J. H. C. Vorsteveld, R. H. Nathan, and H. J. Hermens, "The NESS Handmaster orthosis: Restoration of hand function in C5 and stroke patients by means of electrical stimulation," *Journal of Rehabilitation Sciences*, vol. 9, no. 3, pp. 86–89, 1996.

[7] A. Prochazka, M. Gauthier, M. Wieler, and Z. Kenwell, "The Bionic glove: An electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia," *Archives of Physical Medicine and Rehabilitation*, vol. 78, no. 6, pp. 608–614, 1997.

[8] J. S. Knutson, M. Y. Harley, T. Z. Hisel, and J. Chae, "Improving hand function in stroke survivors: a pilot study of contralaterally controlled functional electric stimulation in chronic hemiplegia," *Archives of Physical Medicine and Rehabilitation*, vol. 88, no. 4, pp. 513–520, 2007.

[9] C. H. Ho, R. J. Triolo, A. L. Elias, K. L. Kilgore, A. F. DiMarco, K. Bogie, A. H. Vette, M. L. Audu, R. Kobetic, S. R. Chang *et al.*, "Functional electrical stimulation and spinal cord injury," *Physical Medicine and Rehabilitation Clinics*, vol. 25, no. 3, pp. 631–654, 2014.

[10] O. A. Howlett, N. A. Lannin, L. Ada, and C. McKinstry, "Functional electrical stimulation improves activity after stroke: a systematic review with meta-analysis," *Archives of physical medicine and rehabilitation*, vol. 96, no. 5, pp. 934–943, 2015.

[11] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilita-

[14] K. Takeda, G. Tanino, and H. Miyasaka, "Review of devices used in

tion," *Journal of neuroengineering and rehabilitation*, vol. 11, no. 1, p. 3, 2014.

[12] P. H. Peckham and J. S. Knutson, "Functional electrical stimulation for neuromuscular applications," *Annu. Rev. Biomed. Eng.*, vol. 7, pp. 327–360, 2005.

[13] B. M. Doucet, A. Lamb, and L. Griffin, "Neuromuscular electrical stimulation for skeletal muscle function," *The Yale Journal of Biology and Medicine*, vol. 85, no. 2, pp. 201–215, 2012.

neuromuscular electrical stimulation for stroke rehabilitation," *Medical devices (Auckland, NZ)*, vol. 10, p. 207, 2017.

[15] J. Fajardo, A. Ribas Neto, W. Silva, M. Gomes, E. Fujiwara, and E. Rohmer, "A wearable robotic glove based on optical FMG controller," in *2019 International Conference on Advanced Robotics and Mechatronics (ICARM)*. IEEE, 2019, Periodical style Submitted for publication 2019.

[16] R. G. Barelli, R. G. G. Piva, R. P. Bechelli, and M. C. F. Castro, "STIMSHIELD - shield para Arduino Uno com dois canais de estimulação elétrica muscular," in *XXV Brazilian Congress on Biomedical Engineering*, H. Vieira Neto, A. B. Soares, and R. P. B. da Costa Félix, Eds., Foz do Iguaçu, Paraná, Brazil, nov. 2016, pp. 412–415.

[17] M. Gouda, "CMSIS-RTOS an API interface standard for real-time operating systems," in *ARM Technology Symposia*, 2012.

[18] J. Liu, S. Li, X. Li, C. Klein, W. Z. Rymer, and P. Zhou, "Suppression of stimulus artifact contaminating electrically evoked electromyography," *NeuroRehabilitation*, vol. 34, no. 2, pp. 381–389, 2014.