Experimental Investigation of Electromyographic Activities of Upper Limb Muscles without and with a Passive Exoskeleton with Four Degrees of Freedoms

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Abstract: *The choice of suitable human surface muscles and of their electromyographic (EMG) signal processing have always been a challenge, especially when technical devices are to be controlled by these signals. Experiments with six healthy volunteers were performed with a NORAXON measuring and processing system. EMG signals from 8 muscles of the upper right arm performing the main motions in the shoulder and elbow joints were registered and processed. Four angles in the joints were also registered. Six motor tasks were performed, without and with an exoskeleton with four degrees of freedom. Since the EMG signal of the muscle pectoralis major was contaminated by noise coming from the electrical activity of the heart, first this signal was filtered using recently developed dynamic filter. Normalization according to maximal isometric tasks was performed after filtration. Rectification and smoothing ensured a suitable signal for proportional control of the exoskeleton. On/off control was simulated by setting different constants for maximal EMG amplitude levels.*

Keywords: *EMG signals, Upper limb, Exoskeleton, Rehabilitation.*

Introduction

People have problems with movements of one or two upper limbs caused by stroke, cerebral vascular incident, spinal cord injures, trauma, sport and occupational injures, etc. The disorders can affect in different degrees shoulder, elbow and wrist joints and fingers. The normal functionality of the upper limbs, i.e. the normal ranges of motion in the joints, co-activity of synergistic and co-contraction of antagonistic muscles is very important for a normal life of disabled persons. A proper rehabilitation can help them to improve the movements. This rehabilitation can be conservative, passive, with a help of physiotherapist, performing different self-dependent exercises. Different technical devices can also be used. There are good and comprehensive surveys on such devices in [4, 9, 18]. The devices can be active or passive orthesis, active exoskeletons, robots [9]. They can have from 1 to 7 degrees of freedom (DOF) [8, 19].

One of the conception of such type of rehabilitation is to move passive, compulsory the upper limb by means of an active exoskeleton with different kinds of drivers – servo motors [27], DC electrical motors [1, 13, 28], pneumatic muscles [14], hydraulic systems [21]. The aim is to train passively the muscles and to increase the ranges of motion in the joints [30]. Thus compulsive movements are imposed to the rehabilitated person's limbs and their muscle control system does not participate anyway. It is known that some brain area is damaged because of the stroke in stroke survivors and descending pathways are interrupted as a result. Brain damage results in corticospinal and supraspinal motor pathway disruption and possibly leads to synaptic degeneration at the segmental level. This loss of neural signaling results in motor neuron loss and in altered muscle force control. This control can be improved by proper rehabilitation because of known neuroplasticity of the nervous human system [32]. Many authors argue that muscle electromyographic (EMG) signals provides information about intention of the person to perform particular movement, i.e. they reflect patient's will [10, 18, 26]. EMG signals, provoked by brain, can be suitable signals for driving exoskeleton constrictions but also can help in establishing new motor pathway. These signals, however, are weak, look like noise and without suitable processing are not able to be used as control signals to the driving systems of technical devices. It has to be noted, however, that muscles of the post-stroke patients, no matter of the way and duration of rehabilitation, have enough distinguished EMG signals of all muscles [3, 24, 25]. The question is which surface muscle to use and how to process the EMG signal.

Son et al. [26] used EMG signals from the muscles biceps brachii and triceps brachii to control flexion/extension in the elbow joint. They filter the signal by Butterworth filter to remove frequencies below 1 Hz and convert this signal to torque of the electrical motor. Phyo et al. [20] reported for a similar device (named RS-6) but they did not mentioned from which muscles the EMG signals were taken. They briefly wrote that the EMG signals (the so called bio-feedback signals) are amplified and processed. Similarly, in [19], where a myoelectrically controlled shoulder-elbow orthosis was described, it was only mentioned that electrodes are placed on the flexor and extensor muscles – nothing was written about the way of processing of the EMG signals. Andreasen et al. [1] described an exoskeleton for assistance of pronation/supination motion in the elbow by using EMG signals from the muscles pronator teres, supinator and biceps brachii. They used calculated mean absolute value of the signal and this value was evaluated for every 30 ms interval. There is no information about type of electrodes, frequency of analog-to-digital converting, information about amplification and filtration (this lack is commonly observed in many papers describing active technical devices for rehabilitation). Much more attention is paid on the EMG signal processing in [15, 16]. They use bipolar surface electrodes to register EMG signal from the muscles biceps brachii and triceps brachii, filter the signals and obtain linear envelope. For so obtained envelope of the two muscles they calculate two constants to recognize properly flexion from extension motion. Besides envelope, an often used method for making noise-like EMG signal suitable for using as control signal, is calculating of root-mean-square (RMS) for some time interval or smoothing by averaging number of samples [22].

In general there are two types of control schemes using EMG signals – proportional and on/off (bang-bang control, binary control, crisp control) [6]. For the first one the control signal is proportional to the amplitude of the processed EMG signal (mainly using the obtained envelope or calculating RMS – [31]). The on-off control presumes a predefined constant level of the amplitude of the EMG signal and if the signal exceeds this level the motor starts to work with a constant velocity, otherwise it is not active.

More detailed consideration of rehabilitation technical devices using EMG as control signals, with more than one degree of freedom is given below. In [12] a 3 DOF mobile exoskeleton is presented which is mounted on a mobile wheelchair. It performs shoulder and elbow flexion/extension and shoulder abduction/adduction using 8 channels of EMG signals for motion control. The muscles from which the EMG signals are taken are: deltoideus (anterior and posterior parts), pectoralis major, teres major, biceps brachii (long and short head), triceps brachii (long and lateral head). The control of the exoskeleton is in real time and it is a combination of flexible fuzzy control and adaptive neural network control. The authors do not use filtration of the EMG signals but only calculate a root mean square value. This type of EMG signal processing is not sufficient since during motions there are big motion artifacts which influence much RMS value. Another problem can be the influence of the electrocardiographic QRS-complex on the EMG signals, recorded from the left muscle pectoralis major. This muscle is very close to the heart and in our experiments [2] we observed high-amplitude heart electrical rhythm. It was mentioned in [12] that when the EMG signals are weak a signal taken from a force sensor placed at the wrist can be suitable for using for control purposes. So, the authors have 3 controllers – force-based, EMG based and obstacle based ones. The last controller prevents from accidental collisions between the user upper limb and the environment. Similar is the mechanics and control of the 4 DOF power-assist exoskeleton in [10], but one more motion is added – elbow pronation/supination. Four muscles are added also into considerations: anconeus, pronator teres, flexor carpi radialis and supinator. These additional muscles are included probably with an aim to estimate the pronation/supination movements in the elbow. The muscle anconeus, however, is very small; it is a synergist of the muscle triceps brachii and acts in synchrony with it. A modification of this exoskeleton is reported in [11]. One similar robot is reported in [7, 8] – the so called SUEFUL-7 – which has even 7 DOF. These degrees of freedom are: shoulder flexion/extension, abduction/adduction and internal/external rotation, elbow flexion/extension and pronation/supination and wrist flexion/extension and radial/ulnar deviation. There are 16 muscle parts from which the EMG signals are taken. Besides the muscles mentioned in [12] 8 muscles more are included – pronator teres, supinator, extensor carpi radialis and ulnaris, flexor carpi radialis and ulnaris, infraspinatus and teres minor. Two measured forces (of forearm and of hand) and forearm torque are also inputs to the controller besides the RMS of the EMG signals. Muscle-model-oriented EMG-based control and/or sensor-based control are realized in this work by using impedance control and neuro-fuzzy modifier. Other approach is reported in [17]. Their 5 DOF (shoulder abduction/adduction and flexion/extension, elbow flexion/extension and pronation/supination and wrist flexion/extension) wearable rehabilitation robot has 5 servo motors. The control signals for these motors come from the EMG signals of the muscles of the healthy upper limb, since the robot is designed primary for stroke survivors with only one injured arm. These muscles are only 4 – biceps brachii, brachioradialis, mid-deltoideus and front-deltoideus, but for each muscle four electrodes are placed. The EMG signals (their mean values) are inputs of a neural network to classify motions.

Recently in the Institute of Mechanics – Bulgarian Academy of Science (BAS) a wearable rehabilitation exoskeleton with 4 DOF (flexion/extension in elbow and shoulder joints, abduction/adduction and rotation interna and externa in the shoulder joint) was developed with pneumatic driving system (artificial muscles) [29]. The intention is to change this driving system with an electric one – servo motors, which will be controlled by EMG signals. The aim of the paper is: to select suitable surface placed muscles, from which EMG signals can be taken and by means of experiments to conclude which signal processing and what control is most appropriate

Methods

Biomechanical considerations

After a detailed survey of the anatomical literature, the main muscles performing the motions in the shoulder and elbow joints were selected [23]. The main requirement was to find surface situated big muscles, predominantly main performers of the motions in the two joints. The results are summarized in Table 1. In bold italic are the muscles chosen for using for exoskeleton control and with * are marked muscles, which assist the motions during a specific upper limb position and can be used as substitutes.

Table 1. Basic muscles performing motions in the shoulder and elbow joints

	Flexion	**Extension**	**Abduction**	**Adduction**	**Rotation interna**	**Rotation externa**
Shoulder joint	***DELcla***	***DELspi***	***DELacr***	***PMJ***	LDO	INF
	BIC	***TRI c. longum***	TRA	LDO	***PMJ***	***DELspi***
	PMJ	TMJ	**_*DELcla_** **_*DELspi_**	***TRI c. longum***	TMJ	
		LDO	*INF p. prox	TMJ	***DELcla***	
			*SEA	**_*DELcla_** **_*DELspi_**		
			*BIC c. longum	*INF p. distalis		
				*BIC c. breve		
Elbow joint	**Flexion**	**Extension**	**Pronation**	**Supination**		
	BIC	***TRI***	***PRO***	***SUP*** *BRD*		
	BRA	*ANC	BRD	***BIC***		
	BRD		*FCR	BRD		
	PRO					

The following abbreviations are used: **DELcla**, **DELspi**, **DELacr** – m. deltoideus, pars clavicularis, pars spinata and pars acromialis; **PMJ** – m. pectoralis major; **BIC** – m. biceps brachii; **TRI** – m. triceps brachii; **PRO** – m. pronator teres; **SUP** – m.supinator; **LDO** – m. latisimus dorsi; **INF** – m. infraspinatus; **TRA** – m. trapezius; **TMJ** – m. teres major; **SEA** – m. serratus anterior; **BRD** – m. brachioradialis; **FCR** – m. flexor carpi radialis; **ANC** – m. anconeus; **BRA** – m. brachialis

It is visible from the table that for each direction of the respective rotation one muscle (prime mover) is chosen: ***DELcla*** performs shoulder flexion; ***DELspi*** – shoulder extension; ***DELacr*** – shoulder abduction; ***PMJ*** – shoulder adduction; ***BIC*** – elbow flexion; ***TRI caput longum*** – elbow extension; ***PRO*** – elbow pronation; ***SUP*** – elbow supination. The muscle ***SUP*** is deeply situated and covered by the muscles extensor digitorum and extensor carpi ulnaris. That is why maybe it will be difficult to record EMG signal from only this muscle (without cross-talk) by surface electrodes. That is why it could be replaced by the muscle ***BRD***. However, muscle ***BRD*** takes participation in both pronation and supination depending on the hand position. Other candidate is the muscle extensor carpi radialis longus, but it is covered by the muscle ***BRD***.

It is also visible from the table that many of the chosen muscles take participation in more than one motion – so they are synergistic or antagonistic with some other muscles which make difficult to juxtapose only one muscle to only one motion. **DELcla** and **DELspi** help in shoulder abduction, caput breve of the muscle **BIC** takes participation in the shoulder flexion and with the common proximal part performs elbow supination; caput longum of the muscle **TRI** takes participation in the shoulder extension and so on.

Experiments

The rehabilitation exoskeleton is shown in Fig. 1 [29]. During the experiments it was detached from the pneumatic driving system, so only the construction weight and friction of the artificial joints affect the motion of the experimental subject (volunteer).

Fig. 1 Exoskeleton design

Six volunteers participated in the experiments, four man and two women, all in good physical condition. The subjects gave their informed consent. They signed an Inform Consent Form. The study was in accordance with the Declaration of Helsinki. The experimental procedure was approved by the Committee of Bioethics of the Institute of Neurobiology – BAS.

The purpose of the experiments was to examine the possibility for obtaining good useful EMG signals from the chosen 8 muscles (DELcla, DELspi, DELacr, PMJ, BIC, TRI, PRO, SUP) and to test the programs for processing the data. The 8-chanel telemetric NORAXON measuring and processing system was used for online monitoring and saving the experiment data for further processing – NORAXON Desktop DTS 8 channels EMG system, NORAXON Myo Motion Research PRO 7 sensor System and MR3.8 Biomedical Analysis Software. The surface EMG signals from the chosen 8 muscles (Table 1) was taken by bipolar Ag/AgCl circle electrodes "Skintact-Premier" F-3010. The skin under the electrodes was cleaned by alcohol. The four angles (three in the shoulder – flexion/extension, adduction/abduction, rotation interna/externa and one in the elbow – flexion/extension) were measured during the experiments. The sampling frequency was 1500 Hz. Hellige EMG conductive gel for better skin-to-electrode contact was used. The electrode locations were determined according to the international guidance (SENIAM project – http://seniam.org/). The EMG signals were preprocessed by the program Biomechanical Analysis Software MR 3.8 of NORAXON Inc. and after that recorded on the hard disk for further processing and analysis. All the signals were transferred wireless to a computer.

The experimental procedure was done in the following steps: (1) reference position (**REF**) – the arm is voluntary relaxed down in the sagittal plane; (2) maximal voluntary isometric contractions aiming to calculate maximal amplitude of the EMG signals for all chosen muscles for further normalization: **MAX1** – for the muscles **BIC, TRI, PRO** and **SUP** and **MAX2** for the muscles **DEL** and **PMJ**; (3) three trials of shoulder flexion/extension (till to 90°) in the sagittal plane starting from the reference position, the thumb points is forward (**FlExSh**); (4) three trials of abduction/adduction in the shoulder joint starting from reference position (**AbAdSh**); (5) three trials of rotation interna and externa in the shoulder joint (**RotSh**) – the initial position of the upper limb is in the horizontal plane – palm is downward; (6) three trials of maximal flexion/extension in the elbow joint in the sagittal plane (**FlExEl**), initial position – reference one. Initially, the experiments were performed without exoskeleton, with placed EMG sensors and sensors for measuring joint angles. After that the exoskeleton was put on carefully, without shifting the sensors. All the movements (Steps 3, 4, 5 and 6) were performed with the right limb, so we have 4 more movements and respective abbreviations: **FlExShEXO, AbAdShEXO, RotShEXO** and **FlExElEXO** respective.

The EMG signals from the 8 channels and the four angles were analog-to-digital converted with sampling frequency of 1500 Hz and saved in text format. Since the EMG signal of the muscle PMJ is accompanied by a noise from the electrical activity of the heart (Fig. 2), this EMG signal was filtered using recently created filter [5]. The maximal absolute values of the EMG amplitude of all muscles during the maximal isometric tasks **MAX1** and **MAX2** (Fig. 3) were calculated and used as normalizing coefficients. All the EMG signals from the performed movements with and without exoskeleton were normalized according to these coefficients. Further the signals were rectified and smoothed with different time constants.

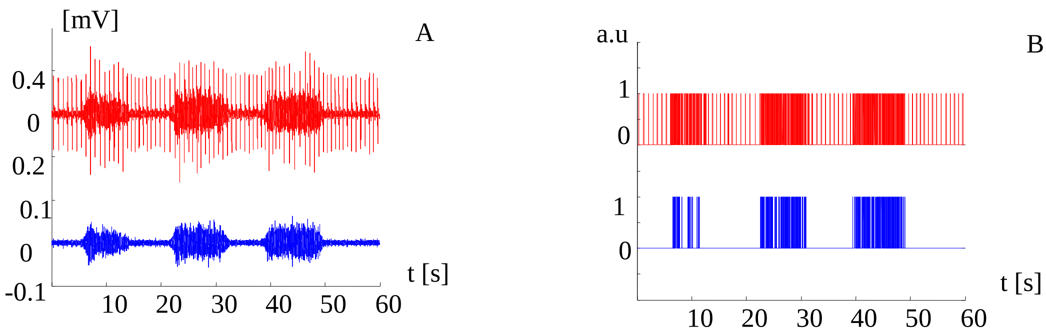

Fig. 2 Effects of filtration of the EMG signal of the muscle PMJ-experiment – **FlExEXO**: A) Red color: EMG signal +ECG noise; blue color: filtered EMG signal; B) Simulation of on/off control – red color noised signal, blue color pure EMG signal after filtration.

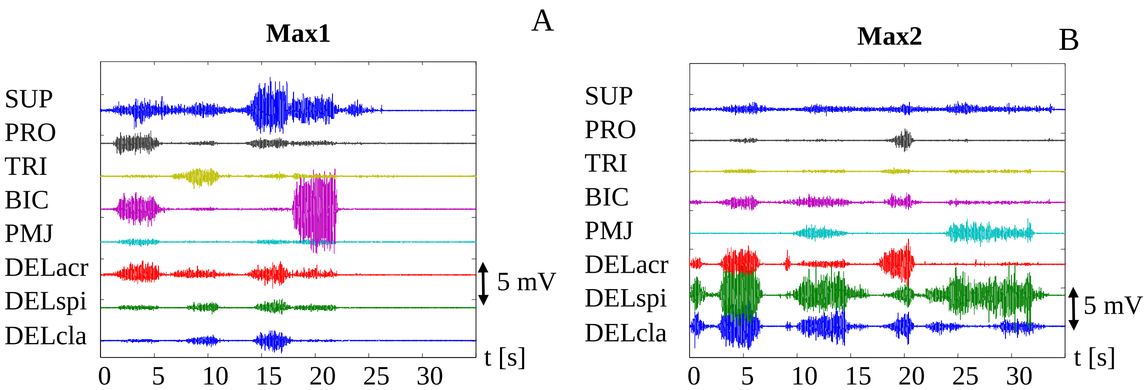

Fig. 3 Row EMG data from the experiments **MAX1** and **MAX2** of one subject

A threshold level was chosen, aiming to model the on/off control of all processed EMG signals. If the filtered, rectified, normalized and smoothed signal for a muscle exceed its level (less than one because of normalization) the control signal is '0', otherwise it is '1'. Different threshold levels were tested.

Results

First, the reference positions for all tested subjects were checked. The angles for this position were set to zero. The EMG signals were checked online using the NORAXON system software for artifacts, the level of the signals was monitored and, if necessary, additional sticking plasters were placed on the electrodes for fixing them better to the skin.

The next two tasks were maximal isometric ones (**MAX1** and **MAX2**) – against a resistance of an operator physiotherapist. For each muscle, a specific static position was chosen and the physiotherapist applied manual resistance in a specific direction. The EMG signals **MAX1** and **MAX2** of the muscle **PMJ** were filtered and their maximal absolute amplitude values were used to calculate the normalization coefficients for each muscle. The next 8 movement dynamic tasks without and with the exoskeleton were processed as follows: filtration of the EMG signal of the muscle **PMJ**, rectification, normalization and smoothing. (Fig. 4A). The on-off control was simulated (Fig. 4B). For the example shown in Fig. 4 the number of samples for smoothing is 10 and the level for "off" signal is 0.1 for every muscle.

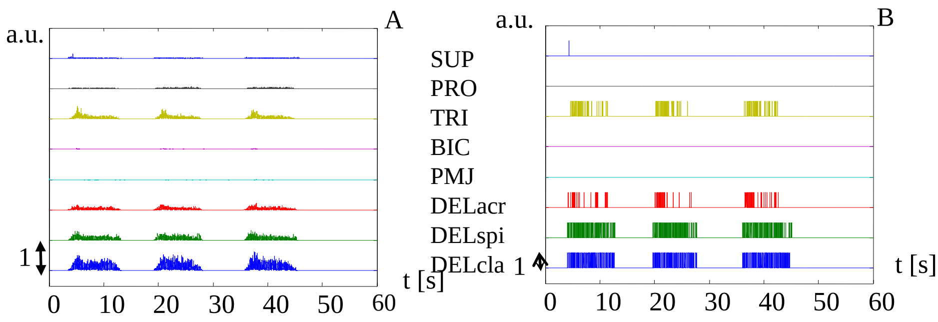

Fig. 4 Three trials of the motion abduction-adduction in the shoulder joint with exoskeleton – **AbAdShEXO**:
A) Filtered, rectified, normalized and smoothed EMG signals of the 8 muscles;
B) Illustration of on/off control – "1" if the signal is higher than 0.1 au, and "0" otherwise.

During the **AbAdSh** and **AbAdShEXO** motions, the three heads of the muscle **DEL** show nearly equal activity. After the abduction movement there is a 5 second break, then the hand relaxes down. However, without looking at the angle, the phases of motion can not be determined. The limb falls slowly down, because of gravity, by increasing the activity of the muscle **DEL**. For one subject slow activity in the muscles **TRI** and **SUP** is observed.

During the **FlExSh** and **FlExShEXO** motions, again most activated DEL muscle parts were **DELspi** and **DELcla.** Muscle **BIC** has also visible EMG activity probably because it is biarticular one and has participation in shoulder flexion.

During the motions **FlExEl** and **FlExElEXO** all muscles show the least activity. This is due to the vertical position of the arm. Besides muscle **BIC,** activities show also the muscles **DELspi** and **SUP** and occasionally **PRO**. So, the elbow flexion is always accompanied by elbow rotation, but it is not possible to recognize when **PRO** and **SUP** are active (sometimes they are active simultaneously). It has to be mentioned that the extensor **TRI** is not active during elbow extension since the forearm falls down under gravity force and the motion is controlled mainly by the modification of the activity of the muscles **DELspi** and **BIC**.

During the motions **RotSh** and **RotShEXO,** the muscle parts **DELcla** and **DELspi** are showing great EMG activity. When exoskeleton is put on, **DELacr** is also included. This is due to the position of the arm which is in the horizontal position. The muscle **SUP** is almost always active and the muscle **PRO** is active only during the motion **RotShEXO**.

The four measured angles were also monitored – Fig. 5 (notice that the vertical axes in Fig. 5A and Fig. 5B are different).

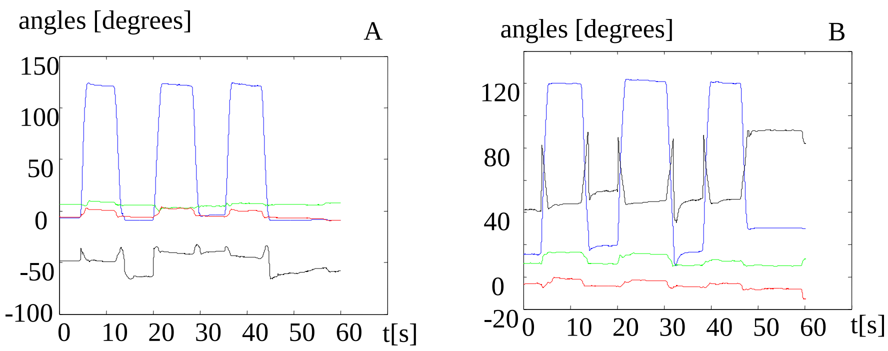

Fig. 5 Joint angles during the motion: A) **FlExEl** and B) **FlExElEXO**.
The following colors are used: blue – elbow flexion/extension;
green – shoulder flexion/extension; red – shoulder abduction/adduction;
black – shoulder rotation interna and externa.

Discussion and conclusions

People perform motions with specific for themselves peculiarities. It is difficult to find unique pattern, both for EMG signals and joint angles. The maximal values of the EMG signals (in mV) differ considerably between the investigated subjects. Independently of this, some general conclusions can be made.

In general, much more muscle force (i.e., EMG activity) is observed when the exoskeleton is put on. Especially this refers to the three head of the muscle **DEL**, which caries all the weight of the mechanical construction. Exception is the motion **FlExElEXO** since here the arm is in a vertical position. Considerable increase of EMG activity is observed when use the exoskeleton. The EMG amplitude is never exceeding the maximal values measured during tasks **MAX1** and **MAX2** (the maximal ismetric tasks). With the exoskeleton the pronation/supination movements are restricted and the muscles **PRO** and **SUP** are less active. The mechanical construction restricts some motions and this is also visible comparing the measured joint angles with and without exoskeleton for one and the same movement.

The muscle **PMJ** is not suitable for using for identification the shoulder adduction. This motion is performed by modulation of the activity of the muscle **DEL**, since the upper arm falls down under the gravity force and no adductor is necessary.

All movements are performed by activities of more than one muscle. This has to be taken into consideration when a mio-control is developed. Measurement of joint angles is suitable to be included in such a control.

EMG records are accompanied by motion and ECG artifacts that obstruct the correct interpretation of EMG signals. Some registration systems, such as NORAXON for example, have built-in filters for motion artifacts. In other systems, motion artifacts are present [2] and are usually suppressed by standard 0-20 Hz high-pass filters. ECG noise is not so easy to filter, because its frequencies overlap the informative EMG frequencies. ECG noise was observed in all recordings of the right upper limb **PMJ** muscle. In most of the cases, the amplitude of the electrocardiographic signal exceeds the amplitude of the EMG signals, which make unfiltered signal not applicable to be used as control signal (see Fig. 2). Standard filters suppressing the ECG are not applicable. Recently we proposed a so-called dynamic filter for separation of electrocardiographic from electromyographic signals [5]. This filter was successfully applied for all our EMG records.

Each person has its specific characteristics of the skin, muscles and other thinks influencing the EMG amplitudes. For example, the maximal amplitudes of one subject for the muscles **DELcla**, **DELspi** and **DELacr** (respectively the coefficients for normalization) were 3.76, 5.46, 3.3 mV for other subject – 1.76, 1.77 and 1.32 mV, respectively. So, simple use of the values of the EMG amplitudes as control variable will lead to mistakes. Normalization of the signals is absolutely necessary. The isometric tasks during which the maximal isometric force will be evoked have to be carefully selected especially for disabled people. So, the main conclusion is that the control of an orthesis device must be strictly personalized. The same refers to the levels of the muscle activity used for on/off control. It has to be mentioned that the simulated on/off control (Fig. 4B) is still not ready to be used as control variable for driving motor.

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References
1. Andreasen D. S., S. K. Allen, D. A. Backus (2005). Exoskeleton with EMG Based Active Assistance for Rehabilitation, Proceedings of the 9th International Conference on Rehabilitation Robotics, June 28 - July 1, 2005, Chicago, USA, 333-336.
2. Angelova S., I. Veneva, R. Raikova, S. Ribagin (2018). Activity of the Upper Limb Muscules during Motor Task without and with an Exoskeleton, Proceedings of the XXVII International Scientific and Technical Conference "Automation of Discret Production Engineering", Sozopol, 208-212.
3. Angelova S., S. Ribagin, R. Raikova, I. Veneva (2017). Power Frequency Spectrum Analysis of Surface EMG Signals of Upper Limb Muscles during Elbow Flexion – A Comparison between Healthy Subjects and Stroke Survivors, Journal of Electromyography and Kinesiology, 38, 7-16.
4. Benitez L. M. V., M. Tabie, N. Will, S. Schmidt, M. Jordan, E. A. Kirchner (2013). Exoskeleton Technology in Rehabilitation: Towards an EMG-based Orthosis System for Upper Limb Neuromotor Rehabilitation, Journal of Robotics, Article ID 610589, 13 pages.
5. Christov I., R. Raikova, S. Angelova (2018). Separation of Electrocardiographic from Electromyographic Signals Using Dynamic Filtration, Med Eng Phys, 57, 1-10.

6. Fougner A., Q. Stavdahl, P. J. Kyberd, Y. G. Losier, A. Philip, P. A. Parker (2012). Control of Upper Limb Prostheses: Terminology and Proportional Myoelectric Control – A Review, IEEE Trans Neural Syst Rehabil Eng, 20(5), 663-677.
7. Gopura R. A. R. C., K. Kiguchi (2008). A Human Forearm and Wrist Motion Assist Exoskeleton Robot with EMG-based Fuzzy-neuro Control, Proceedings of the 2nd IEEE RAS&EMBS, International Conference on Biomedical Robotics and Biomechatronics, Scottsdale, 550-555.
8. Gopura R. A. R. C., K. Kiguchi, Y. Li (2009). SUEFUL-7: A 7DOF Upper Limb Exoskeleton Robot with Muscle-model-oriented EMG-based Control, IEEE/RSJ International Conference on Intelligent Robots and System, St. Louis, 1126-1131.
9. Islam R., C. Spiewak, M. K. Rahman, R. Fared (2017). A Brief Review on Robotic Exoskeletons for Upper Extremity Rehabilitation to Find the Gap between Research Prototype and Commercial Type, Advances in Robotics & Automation, 6(3), 1-12.
10. Kiguchi K. K., Y. Imada, M. Liyanage (2007). EMG-based Neuro-fuzzy Control of a 4DOF Upper-limb Power-assist Exoskeleton, Proceedings of the 29th Annual International Conference of the IEEE EBS, Lyon, France, August 23-26, 3040-3043.
11. Kiguchi K., M. H. Rahman, M. Sasaki (2005). Motion Control of a Robotic Exoskeleton, Proceedings of the International Conference of Information and Automation, Colombo, Sri Lanca, December 15-18, 186-191.
12. Kiguchi K., M. H. Rahman, M. Sasaki, K. Teramoto (2008). Development of a 3DOF Mobile Exoskeleton Robot for Human Upper-limb Motion Assist, Robotics and Autonomous Systems, 56(8), 678-691.
13. Kiguchi K., Y. Kose, Y. Hayashi (2010). Task-oriented Perception-assist for an Upper-limb Power Assist Exoskeleton Robot, Proceedings of the World Automation Congress, TSI Press, Kobe, Japan, 6 pages.
14. Kline T., D. Kamper, B. Schmit (2005). Control System for Pneumatically Controlled Glove to Assist in Grasp Activities, Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics, June 28 - July 1, Chicago, USA, 78-81.
15. Lenzi T., S. M. M. De Rossi, N. Vitiello, M. C. Carrozza (2011). Proportional EMG Control for Upper Limb Powered Exoskeletons, Proceedings of the 33th Annual International Conference of the IEEE EMBS, Boston, Masachusetts, USA, August 30 - September 03, 628-631.
16. Lenzi T., S. M. M. De Rossi, N. Vitiello, M. C. Carrozza (2012). Intention-based EMG Control for Powered Exoskeletons, IEEE Trans Biomed Eng, 59(8), 2180-2190.
17. Li Q., D. Wang, Z. Du, Y. Song, L. Sun (2006). sEMG Based Control for 5 DOF Upper Limb Rehabilitation Robot System, Proceedings of the 2006 IEEE International Conference on Robotics and Biomimetics, Kunming, China, December 17-20, 1305-1310.
18. Maciajasz P., J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, S. Leonhardt (2014). A Survey on Robotic Devices for Upper Limb Rehabilitation, Journal of Neuroengineering and Rehabilitation, 11:3.
19. Ogce F., H. Ozyalcin (2000). A Myoelectrically Controlled Shoulder-elbow Orthosis for Unrecovered Brachial Plexus Injury, Prosthetics and Orthotics International, 24, 252-255.
20. Phyo S. T., L. K. Kheng, S. Kumar (2016). Design and Development of Robotic Rehabilitation Device for Post Stroke Therapy, International Journal of Pharma Medicine and Biological Sciences, 5(1), 31-37.
21. Pylatiuk C., A. Kargov, I. Gasier, T. Werner, S. Schulz, G. Brethauer (2009). Design of a Flexible Fluidic Actuation System for a Hybrid Elbow Orthosis, Proceedings of the IEEE 11th International Conference on Rehabilitation Robotics, Kyoto International Conference Center, Japan, June 23-26, 167-171.

22. Rahman M. H., C. Ochoa-Luna, M. Saad, P. Achambault (2015). EMG Based Control of a Robotic Exoskeleton for Shoulder and Elbow Motion Assist, Journal of Automation and Control Engineering, 3(4), 270-276.
23. Raikova R. (1992). A General Approach for Modelling and Mathematical Investigation of the Human Upper Limb, J Biomech, 25(8), 857-867.
24. Raikova R., S. Angelova, S. Ribagin (2016). Changes in EMG Activities of Upper Arm Muscles and in Shoulder Joint Angles in Post-stroke Patients, International Journal Bioautomation, 20(3), 389-406.
25. Raikova R., S. Angelova, V. Chakarov, D. S. Krastev (2014). An Approach for Experimental Investigation of Muscle Activities of the Upper Limbs (Right versus Left Arm) of Healthy Subjects and Post-stroke Patients – A Preliminary Study, International Journal Bioautomation, 18(2), 101-110.
26. Son J. S., J. Y. Kim, S. J. Hwang, Y. Kim (2009). The Development of an EMG-based Upper Extremity Rehabilitation Training System for Hemiplegic Patients, Proceedings of the 13th International Conference on Biomedical Engineering, IFMBE, Lim C. T., J. C. H. Goh (Eds.), Vol. 23, Springer, Berlin, Heidelberg, 1977-1979.
27. Song R., K. Tong, X. Hu, L. Li (2008). Assistive Control System Using Continuous Myoelectric Signal in Robot-aided Arm Training for Patients After Stroke, IEEE Transactions of Neural Systems and Rehabilitation Engineering, 16(4), 371-379.
28. Tiboni M., A. Borboni, R. Faglia, N. Pellegrini (2018). Robotics Rehabilitation of the Elbow Based on Surface Electrimy Ography Signals, Advances in Mechanical Engineering, 10(2), 1-14.
29. Veneva I., D. Chakarov, P. Venev, E. Zlatanov, M. Tsveov, D. Trifonov, X. Navaro (2018). Exoskeleton for Rehabilitation, Problems of Engineering Cybernetics and Robotics, 69, 30-39.
30. Vitiello N., T. Lenzi, S. Roccella, S. M. M. De Rossi, E. Cattin, F. Giovacchini, F. Vecchi, M. C. Carrozza (2013). NEUROExos: A Powered Elbow Exoskeleton for Physical Rehabilitation, IEEE Transactions on Robotics, 29(1), 220-235.
31. Wang L., H. Li, F. Meng (2015). Study on Upper Limb Rehabilitation System Based on Surface EMG, Bio-medical Materials and Engineering, 26, S795-S801.
32. Wilkins K. B., M. Owen, C. Ingo, C. Carmona, J. P. A. Dewald, J. Yao (2017). Neural Plasticity in Moderate to Severe Chronic Stroke Following a Device-assisted Task-specific Arm/Hand Intervention, Front Neurol, 8, 284.

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