Proceedings of the 2007 IEEE
International Conference on Robotics and Biomimetics
December 15 -18, 2007, Sanya, China

Electromyography Sensor Based Control for a Hand Exoskeleton

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***Abstract*—This paper presents a electromyography (EMG) control for a hand exoskeleton. The device was developed with focus on support of the rehabilitation process after hand injuries or strokes. As the device is designed for the later use on patients, which have limited hand mobility, fast undesired movements have to be averted. Safety precautions in the hardware and software design of the system must be taken to ensure this. The construction allows controlling the motion of finger joints. However, due to friction in gears and mechanical construction it is not possible to move finger joints within the construction without help of actuators. Therefore force sensors are integrated into the construction to measure force exchanged between human and exoskeleton. These allow the human to control the movements of the hand exoskeleton which is useful to teach new trajectories, for muscle training, or for diagnostic purposes. The control method using electromyography (EMG) sensor presented in this paper uses the EMG sensor values to generate a trajectory, which is executed by a position control loop based on sliding mode control.**

***Index Terms*—rehabilitation, exoskeleton, orthesis, control, EMG**

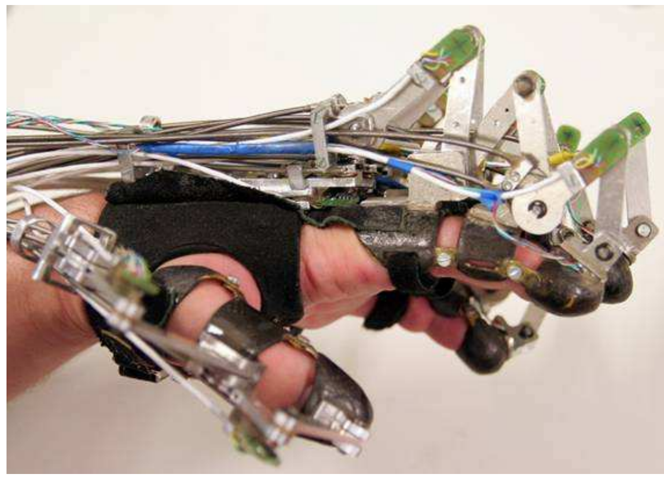

Figure 1. Prototype of the hand exoskeleton attached to the authors hand. Four fingers are actuated in four joint axes per finger. The force is transmitted through pull cables to the finger joints. Hall sensors are attached to the levers to measure joint angles.

I. Introduction

After injuries of the hand or surgery, a rehabilitation process is necessary to regain as much dexterity back as possible. For example, rehabilitation can be required to prevent agglutination or adhesion of the involved tissue. After long periods of being unable to use the hand, it may also be required to relearn basic movements. This is also important for stroke patients. The rehabilitation process is time-consuming and labour-intensive, making the process expensive. If the rehabilitation is not performed optimal, the consequences can be serious. Especially limited hand dexterity can be a big problem for affected persons.

Machines can support the process of rehabilitation. Currently only simple machines are available [1]. These apply a continuous motion to the finger joints. The flexibility of these devices is limited; they support only few independent degrees of freedom and provide no sensor data as feedback for therapists. Exoskeletons could provide a more flexible support for rehabilitation.

Exoskeletons are devices with external joints and links which correspond to those of the human body. Often only a few joints of parts of human body are supported, such as in hand exoskeletons or leg exoskeletons. Attached to the human body it is possible to exert torques to some of these joints by actuators, while other may only are passively moving. Especially exoskeletons with only passive joints are sometimes called orthesis.

Two basic construction principles are common. The Rutgers Hand Master II uses pistons mounted inside the palm which prevents interaction with real objects, but allows a simpler construction [2]. Other exoskeletons do not have mechanical elements inside the palm and allow interaction with the environment (e.g. [3]).

Hand exoskeletons used in virtual reality application look promising at first, but lack some important features that are essential for rehabilitation. These devices often apply force only into one direction, whereas bidirectional force application is desirable for rehabilitation. Some only use brakes to restrict the motion. To simulate contacts in a virtual environment this is convenient and even safer than moving the joint actively [4]. However, for patients incapable to move their hands it is unsuited. Some other hand exoskeletons already have shown to be useful during rehabilitation [5] or [6], although the number of actively powered joints is relatively low.

One the basis of these findings a hand exoskeleton shown in Fig. 1 was developed. Altogether sensing and movements in 20 degrees of freedom is supported. Each finger is sup-

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ported in four degrees of freedom: Flexion and extension in metacarpophalangeal (MCP) joint, proximal interphalangeal (PIP) joint, and distal interphalangeal (DIP) joint; and abduction/adduction in MCP joint. The thumb can also be moved in four degrees of freedom. The carpometacarpal joint (CM) is support in flexion/extension and in abduction/adduction movement, metacarpohalangeal (MC), and the interphalangeal (IP) joint are supported in their flexion movement. The palm is free of mechanical elements and bidirectional movement is allowed. This system is described in detail in section II.

Different control strategies are necessary to support rehabilitation effectively. Position control is needed for joint mobilisation. An efficient position-based control strategy for the hand exoskeleton based on sliding mode control was previously presented in [7] and a force based control was presented in [8]. EMG control is motivated in section III, details of the EMG control algorithm implemented for the hand exoskeleton is described in section IV. Prelimary experimental results are shown in section V.

II. System Description

The system is designed to support up to 20 finger joints four for each finger. Fig. 1 shows an overview of the hand exoskeleton system. User interface is seperated from the real-time controller which is responsible for the control loop and data aquisition. The hardware watchdog monitors the real-time controller and disables the PWM amplifiers if a time out failure occures. Details of the safety measures to ensure the safety of the system are described in [9].

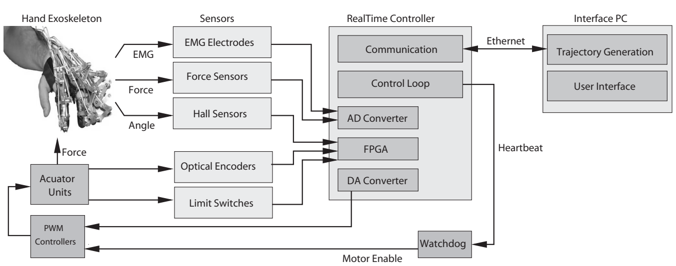

Figure 2. System overview of the hand exoskeleton system used for the experiments.

A. Sensors of the system

The system is equipped with following sensors:

- Hall sensors to measure joint angles
- Optical encoders to measure angles of motor axes
- Force sensors measuring the force between human and construction
- Surface Electromyograph sensors at the forearm

To provide angular measurement the angle of the levers of the construction are measured by hall sensors (*KMZ41 from Philips*) which are evaluated by integrated circuits (*UZZ9001 from Philips)*. These can be read-out through the serial peripheral interface (SPI). On the other side of the construction optical quadrature encoders (*from Maxon*) are used to measure the position of the motor axes. The values for the calculated joint angles deviate because of varying tension of the Bowden cables. Due to this redundant measurement, it is possible to detect mechanical failure by comparing these values. The joint angle measurement is implemented for all joints.

In addition to the joint angle measurement, force sensors (*Entran ELFS-B3-50N*) are integrated into the construction. The sensors are placed between the finger attachments and the levers and thereby measure the force transferred from the human to the construction. Due to mechanical reasons the angle of the force application to the sensor varies from about 70 to 40 degrees. Because sensors in use are calibrated for perpendicular force application, measured forces have to be corrected depending on the joint angles. Currently only the finger tips are equipped with force sensors.

Electromyography (EMG) electrodes can measure the electric activity at the skin of up to sixteen muscles. The electrodes (DE-2.3 MyoMonitor from DelSys) have an integrated low noise amplifier which amplifies the signal by the factor of thousand (1000 V/V) and are equipped with a bandpass which limits the signals to 20 - 450 Hz.

For safety reasons the EMG sensors signals are not directly connected to the ADC of the real-time controller. The signals are digitized by 16 Bit ADCs (MAX1168 from Maxim). The digital interface of the used ADCs is an serial periphal interface (SPI). For safety reasons electrodes and ADC are powered by rechargeable batteries and the data lines of the SPI are galvanically insulated. Because of the high number of muscles in the forearm, recorded signals are superimposed. To improve the signal quality methods of blind source separation can be applied.

B. Actuator setup

The joints are driven through Bowden cables by standard DC motors. Bidirectional movement is supported by the use of two pull cables for each joint diverted by a pulley on both ends. Only one motor for each joint is used, which introduces some slackness compared to the solution using one motor for each direction. The motion is applied through a leverage construction onto each finger attachment. Details of the construction are described in [10].

Standard PWM controllers (*4122Z from Copley Controls*) drive the motors on the remote side of the Bowden cables. These controllers are used in torque control mode and are driven by analogue inputs. Current monitor output allows observation of the PWM controller operation. By using an emergency switch, the power supply can also be interrupted at any time.

III. EMG Control

Human-machine interaction is often implemented by using force sensors. The hand exoskeleton also uses force control to allow the human to influence movements of the hand exoskeleton. Without this control possibility friction of the gears would restrict movements considerable, but the hand exoskeleton must be able to follow the movement of the human. This allows measuring the motions of the hand without the load of the additional friction (e.g. for assessment of rehabilitation progress). Another use is the teaching of movements (e.g. for joint mobilisation). The force control can also increase the necessary force for movements for training possibilities. Force control strategy was based on the underlying sliding mode control was presented in [8].

One problem of the human-machine interaction is that the force sensors integrated into the construction do not distinguish between forces exerted by the user and external forces. During contact with the environment it becomes impossible to recognize the user's intention. Additional force sensor at every possible contact surface could detect possible collisions with the environment. Alternatively the human motion intention can be detected by acquiring the physiological muscle signals, e.g. the electromyographical (EMG) signals by sensors.

The control of hand prosthesis with EMG signals is quite common, see e.g. [11], [12], or [13]. Often in these works do not use muscles which where originally responsible for the motion (e.g. the biceps in [14]). The reason for not using these muscles, is that they are often injured, degenerated, or it is complicated to measure them. Some authors try to control robotic hands by EMG signals, e.g. [15]. These devices require some learning of the user. Patients using this exoskeleton usually will still have functional muscles and temporarily learning to use other muscles for the control of the hand exoskeleton may have negative consequences. Using EMG control for exoskeletons also result in a force feedback to the user, where prosthesis do not have such a feedback. Therefore, muscles that are responsible for the controlled movements should be used control the hand exoskeleton. The control of hand exoskeletons using EMG signals is very seldom done. One example for using muscles of the forearm to control a finger exoskeleton in one degree of freedom is shown in [16].

A small overview of the possibilities of EMG controlled exoskeletons was presented in [17]. Two approaches of EMG control for a leg exoskeleton were explained and the potential of EMG control for hand exoskeletons was discussed. One approach to control hand exoskeletons movements by using EMG signals is presented in this paper.

IV. CONTROL ALGORITHM

EMG sensor data can be used to control the hand exoskeleton without measuring all contact forces. However, there are several difficulties in the application of the algorithms. The first problem is that not all muscles responsible for the hand motion can be measured by surface EMG sensors. Only a subset of the muscles responsible for the finger and hand movement is sampled by surface electrodes. Therefore, it is not possible to use the EMG signals alone to control arbitrary motions in all supported degrees of freedom.

The second problem is that due to the high density of different muscles at the forearm, the EMG signal separation problem is particular relevant. The signals have to be processed to recover the underlying original signals. Blind source separation can be used to solve the problem. After an ideal separation, the signals could be used for control purposes. Physicians can also use the recovered muscle signals together with motion and force data for diagnosis.

After the blind source separation of neighbouring channels additional steps are necessary. The signals are rectified and low-passed before an additional decomposition which uses the inverted mixing matrix which is derived during a calibration procedure. The demixed signals are assigned different degrees of freedom. After applying a threshold a simple EMG signal translation is performed. Force contributions of muscles that are not measured by EMG sensors have to be estimated by other means. For example the force contribution can be derived from other measured muscle signals by assuming a specific movement. Resulting forces are used to generate a trajectory which is executed by the position control. Fig. 3 shows the scheme of the proposed EMG control for the hand exoskeleton device.

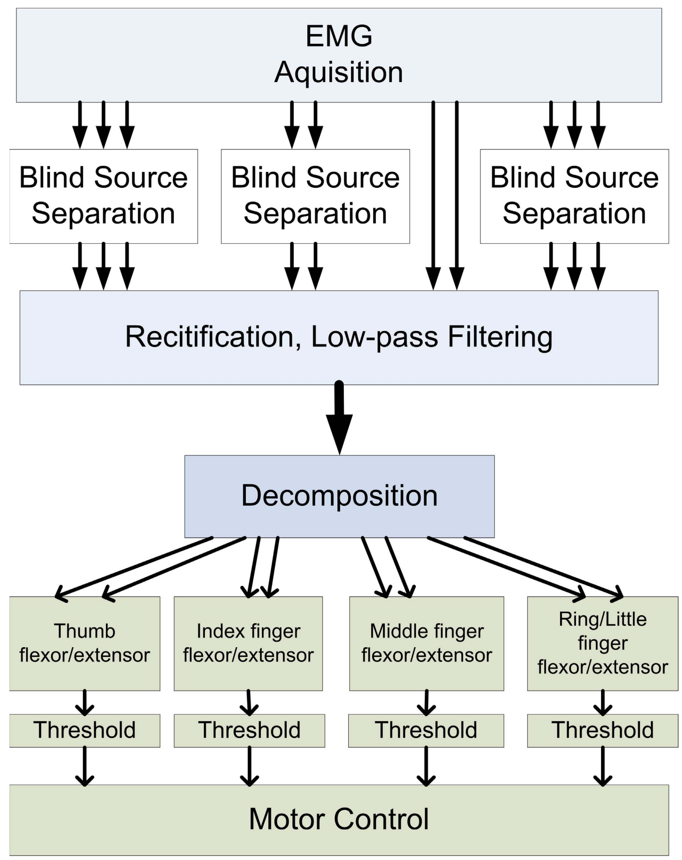

Figure 3. Scheme of the EMG control for the hand exoskeleton device. After signal acquistion a blind source separation of neighbouring channels is performed. The signals are then rectified and low-passed before an additional decomposition tries to assign the recorded signals to different intended movements. The resulting signals are distributed to the different degrees of freedom and a trajectory is generated which is executed by the motor control.

A. Muscle Selection

The muscle selection and sensor placement is difficult problem. The human hand has up to 40 muscles which influence the hand and wrist movement. Some of them are also split into muscle compartments. These muscles are either located at the forearm and the intrinsic muscles are located in the palm of the hand. Due to the limitation of space only muscles of the forearm are measured.

The muscles of the forearm are arranged in several layers making it difficult to measure their signal by surface EMG electrodes. The density of the muscles is high resulting the muscle signals to superimpose at the electrodes.

Following sensor locations were selected for measurement at the palmar forearm:

- *M. flexor digitorum superficialis* near wrist (two electrodes)
- *M. flexor policis longus* (one electrode)
- *M. flexor digitorum superficialis* middle section of forearm (one electrode)
- *M. flexor digitorum superficialis* upper section of forearm (one electrode)

Following sensor locations were selected for measurement at the dorsal forearm:

- *M. Extensor digitorum* (three electrodes)
- *M. Extensor pollicis longus* (one electrode)
- *M. Extensor indicis* (one electrode)

The *flexor digitorum superficialis* is responsible for finger flexion at MCP and PIP joints. The *flexor digitorum profundus* and some intrinsic muscles of the hand are also responsible for finger flexion, but these muscle are either not at the surface or covered by the mechanical construction and therefore currently not measurable by using surface electrodes.

The *flexor policis longus* is partly responsible for the flexion of the thumb, while the *extensor pollicis* is responsible for the extension. The *extensor digitiorum* is responsible for the extension of all digits, and *extensor indicis* is only responsible for the extension of the index finger. Other muscles influence these motions as well but are not easy measurable by surface electrodes. Fig. 4 illustrates the sensor locations on the forearm.

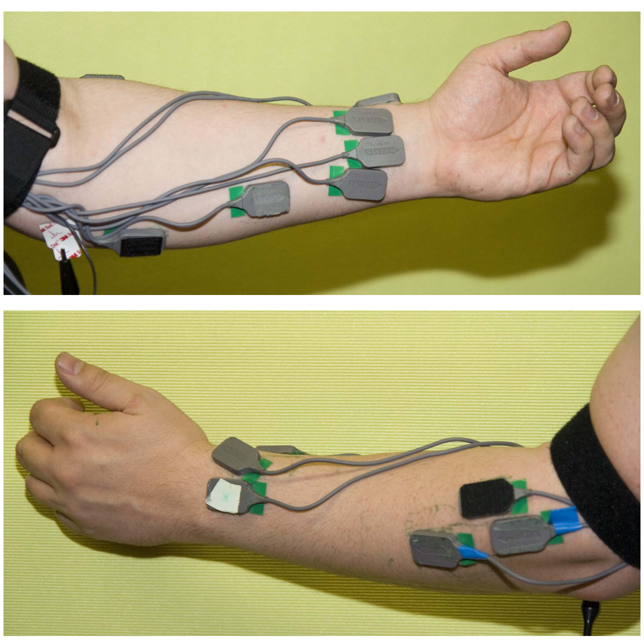

Figure 4. Picture of the palmar and dorsal side of the forearm illustrating the EMG sensor locations (without the hand exoskeleton attached).

B. Blind Source Separation

To increase the signal separation a blind source separation with low latency was used. A linear instantaneous mixing was assumed:

$$y(t) = B\,x(t) \tag{1}$$

The signals are filtered by a weighted low-pass differential filter. The inverse demixing matrix is then approximated by an iterative algorithm described in [18] (EASI). By using these algorithms a separation of about 1.5dB for neighbouring sensors can be achieved. More distant sensors can not be separated by this algorithm due to possible time delay and non-linearities of the mixing process.

However, the algorithm does not converge for high muscle activation, therefore the mixing matrix is only updated if the muscle signals are below ten percent of the maximum volatile contraction (MVC).

After the blind source separation the signal is rectified and low-pass filter at 10 Hz.

C. Muscle Signal Decomposition

Even after the blind source separation the signals are not separated ideally. Therefore an additional step is implemented to achieve muscle signal decomposition for the different degrees of freedom. The goal is to achieve a one degrees of freedom control for each finger. To accomplish this one extensor and one flexor signal for each degrees of freedom have to be separated. During early experiments it turned out, that it is not possible to separate the muscle signals from the ring finger and little finger. Therefore both fingers are expected to perform the same movement. The other fingers including the thumb are assigned to individual movements. One additional limitation is introduced: the wrist should not be moved and no pronation or supination movement occurs as the muscle signals change for different hand postures.

For the muscle signal decomposition again a simplified assumption of linear mixing is made. The individual movements of each finger are performed and feature vector is identified. These feature vectors are combined to a mixing matrix which is inverted for the decomposition process. Multiplying the previously processes signals results in a vector which holds the calculated activation for the flexion and extension of the different degrees of freedom. These values represent not the true activations, but can be used for the trajectory generation after applying a threshold.

D. Trajectory Generation and Control

Only a few muscles responsible for the motions of the hand are measured. Therefore it is not possible to use an accurate biomechanical model to translate the muscle activation signals to force for the different degrees of freedom. Instead a very simple model is assumed, where each finger is in its relaxed position when no muscle activation is measured. Depending on the muscle activation a linear force is calculated and the fingers are moved as if acting against a constant friction. The different flexion and extension degrees of freedom in MCP, PIP, and DIP joint are assumed to perform a coupled motion.

$$x = x_0 + \frac{(F_{flex} - F_{ext})\tau}{B} \tag{2}$$

, where B is the simulated friction, $x_0$is the previous position, τ is one time step, and F_{flex} and F_{ext} is the force calculated based on the flexion and extension activation of the muscles. The forces are set to zero below a threshold and then grow proportional after reaching the threshold.

This generated trajectory is then executed by the underlying position controller which is based on sliding mode control presented in [7] and therefore very robust for parameter variations and varying loads.

V. Experimental Results

The recorded surface EMG signals for ten channels are shown in Fig. 5 and 6. The motions performed for these tests were flexion and extension of the thumb, index finger, middle finger, ring finger, and little finger. The different motions are just barely distinguishable by visual inspection. Some EMG signals are easily distinguishable, e.g. in Fig. 6 the middle finger flexion (third movement) results in a strong signal at the second EMG channel on the flexor side. The flexion of the ring finger in the same diagram shows a strong signal at the first EMG channel, but produces only a very small signal at the location of the second EMG electrode.

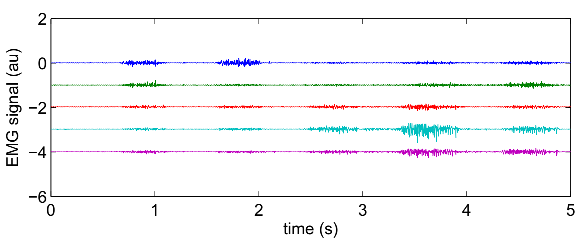

Figure 5. Recorded EMG signals of five channels measured at different sensor locations for the extension. Five different motions are performed. The recording shows thumb, index finger, middle finger, ring finger, and little finger extension.

Some movements are not clearly distinguishable. For example the extension of the index finger (second movement in Fig. 5) generates a relatively strong signal at the location of the first EMG sensor on the extensor side, but a signal of similar strength is generated during the extension of the thumb). The reason is due to the very small distance of the sensor and muscles. But the signals are still different because the second channel is more activated at the thumb motion than during the index finger motion.

Especially the motion of the little finger is not clearly visible in the EMG signals, as it generates more of less small amplitude EMG signals at all sensor locations. This may be caused by the fact that less muscle power is used and that it is not possible to move the little finger alone. Co-activation of other muscles is therefore present. As mentioned in section III, the little finger will be considered as a coupled to the motion of the ring finger.

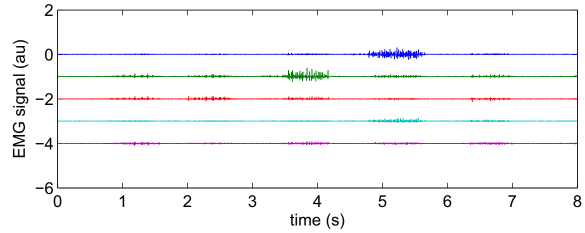

Figure 6. Recorded EMG signals for five channels measured at different sensor locations for the Flexion. Five different motions are performed.The recording shows thumb, index finger, middle finger, ring finger, and little finger flexion.

Generally for each motion a feature vector could be calculated during the calibration where each degrees of freedom had to be moved separately in flexion and extension as the recorded motion shown in Fig. 5 and 6. These vectors were used to form a mixing matrix, and the inverse was used to perform a demixing process.

The signals shown in Fig. 5 and 6 were then processed by the algorithm described in the previous section. The blind source separation step is currently not included into the real-time processing, but the control works also without this processing step. The different intermediate steps of the signal processing are not shown here due to the restricted space.

Finally this activation was used to generate a trajectory which was then executed by the underlying position control algorithms. The resulting trajectories for the movement of the thumb and index finger are shown in Fig. 7. It can be seen that it is possible to perform a selective motion for both finger, but a small overshooting occurred during the end of the motion. Additionally, it was not always possible to perform the motion which was intended as can be seen in Fig. 7, because the other finger are also moving to a lesser degrees when one finger is moved. However, also the natural human finger movements are coupled to some degrees.

During experiment it was noticed that integrating of additional sensors and additional degrees of freedom the calibration and the subsequent demixing process became more complex and the positioning of the electrodes became more critical. If the placement of the electrodes was not good, the feature vectors for the motions were too similar and no demixing was possible. The EMG sensor placement is critical to achieve good results, sometimes an EMG electrode placed a centimetre different can give different results.

The quantitative evaluation of experimental results is difficult, because it is hard to judge to what extent the movements of the hand exoskeleton reflect the intended movement of the user. Because the limited number of individual degrees of freedom the movement will not reflect exactly the intended motion, as movements in other degrees of freedom are only derived from the other degrees of freedom. Only a movement similar to the intended movement will be performed. The measured force from the force sensors will are not expected to be zero, which would be the case if the hand exoskeleton follows the movement of the hand as long the is no contact with the environment.

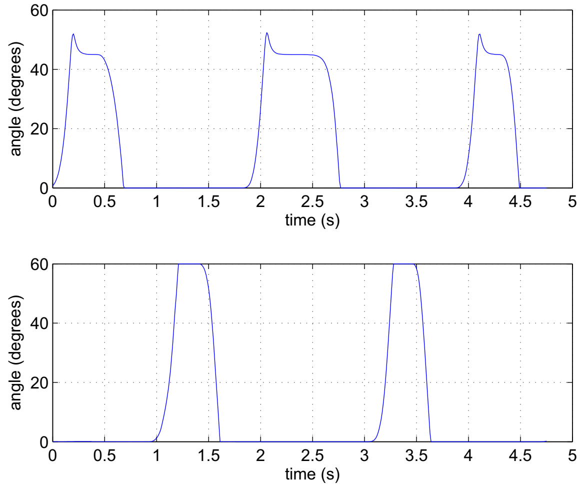

Figure 7. Resulting motion based on the recorded EMG signals. First figure shows the resulting motion of the thumb, the second figure shows the resulting motion of the index finger while trying to move both independently.

VI. Conclusions and Outlook

An EMG signal control scheme was presented to control four degrees of freedom with ten surface EMG sensors. Experiments show that the proposed control scheme allows controlling the movements of the hand exoskeleton. The preliminary results indicate that the performed movement were the intended movements.

Due to several limitations the current control scheme is not very practical. First, electrode placement is critical and takes considerable amount of time. Additional, no wrist movement should occur and pronation and supination should be avoided.

A matrix of many EMG sensors and improved algorithms for signal separation could overcome these problems. With more EMG sensors it would become possible to measure more muscles and maybe even use a biomechanical model to calculate the intended motion and then execute this based on an inverse dynamic model of the hand or to control the individual joints. It would be possible to assess the force capabilities of the muscles and use this for diagnosis of neuromuscular diseases.

Double differential electrodes could improve the signal separation significantly and therefore increase the performance as well.

Very important is a better initial calibration of the whole system including the possibility to allow wrist motion and pronation and supination of the forearm. This calibration could be achieved e.g. by artificial neural networks which correlate the measured movement and forces of the hand exoskeletons with the measured EMG signals.

An improved control algorithm could even create more force then intended by the user to increase the force abilities of the user, which would be helpful for patients with weak muscles.

Another possibility is the suppression of undesired movements (e.g. because of a tremor) during the rehabilitation therapy [19] which could disturb the rehabilitation progress.

Acknowledgements

This project is supported by the German Research Foundation (DFG).

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