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Changes in Muscle Activation Patterns Following Robot-assisted Training of Hand Function after Stroke

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Abstract—**Robot-assisted rehabilitation has only recently begun to be applied to improvement of hand function after stroke. In a preliminary study, involving 4 post-stroke subjects, more than 2 years following the stroke, we have been able to show that 8 weeks of robot-assisted training leads to changes in patterns of arm and finger muscle activation. The patterns were quantified in terms of synchronous muscle synergies which allowed for comparison with muscle activation patterns of healthy age-matched subjects. We found that the muscle synergies of the post-stroke subjects became more similar to those of the healthy subject group following training.**

I. Introduction

Weakness, spasticity and abnormal patterns of muscle activation are common after stroke. The greatest weakness relative to normal occurs in wrist and finger flexor muscles [1]. Hemiparetic stroke is usually also accompanied by abnormally high muscle tone (identified as spastic hypertonia or spasticity) and abnormal patterns of synergistic muscle activation, in the form of compulsory co-activation of either anatomical flexors or extensors at multiple joints, although synergistic activation of flexors is more common [2]. Subjects with finger flexor spasticity were found to have difficulty in extending the fingers both because of reduced voluntary activation of extensor muscles and coactivation of finger flexors [3]. Thus, apparent weakness may be partly due to an inability to inhibit antagonist muscles. Such abnormal antagonist activation may increase weakness by limiting agonist muscle activation.

Strength [1] and spasticity [3] of the affected hand can be quantified to provide comparative measures of the effectiveness of rehabilitation prior to and after treatment. However, it is less straightforward to quantify changes in muscle activation patterns. Wrist and finger muscle activation patterns during functional activities following stroke, abnormalities in these patterns resulting from the stroke and changes in these patterns from pre- to post-rehabilitation have yet to be described in quantitative terms. To be meaningful, these descriptions should include activity from multiple muscles, recorded during movements which are relevant to activities of daily living.

Several robotic devices have been developed recently for hand rehabilitation, which require subjects to perform movements of the hand that are functionally relevant to ADL [4]-[12]. Because both motion and force can be accurately measured by robotic devices, rehabilitation exercises can be rigorously controlled, ensuring that muscle activation can be compared for virtually identical tasks before and after training. Using two new rehabilitation robots, the HandCARE [11] and the Haptic Knob [12], we have conducted a pilot study with stroke survivors in which we examined changes in patterns of activity of hand and arm muscles following 8 weeks of specialized training. To determine whether muscle activation patterns become more like normal activation patterns following training we compared pre- and post-training EMG of stroke survivors with that of age-matched control subjects using the concept of muscle synergies.

Muscle synergies have taken on different meanings in the context of theories of motor control and neurorehabilitation [13]-[16]. In the context of motor control, synergies are the building blocks of movements. Each synergy comprises a muscle activation pattern, i.e. a specific relative activation for each muscle. In the context of neurorehabilitation, synergies are stereotyped movements of a limb resulting from loss of independent control of muscles at different levels, e.g. joints. They are typically classified as flexor or extensor depending on which muscle group is dominant. Despite these differences in the way synergies have been defined the analysis techniques developed for determining synergies in the context of normal motor control [13], [14] can be used to address the issue of changes in muscle activation following rehabilitation.

Two different models for re-constructing muscle activation patterns have been proposed using the concept of muscle synergies [3],[17]. In one case, instantaneous muscle activation patterns are re-constructed by combinations of time-varying muscle synergies which are independently scaled in amplitude and shifted in time. In the other, time-varying combinations of nonnegative constant vectors

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are used instead (synchronous muscle synergies). Using the latter method we were able to show that muscle activation patterns more closely resembled those of age-matched healthy subjects after than before robot-assisted rehabilitation of hand function. We selected synchronous versus time-varying muscle synergies for our analysis because of two reasons: *i*) by using synchronous muscle synergies we were able to investigate at each time step which muscles are added (activated concurrently) or eliminated from a normal pattern of muscle synergy and *ii*) synchronous muscle synergies do not depend on the duration of the movement, unlike time varying muscle synergies. Since the duration of movements performed by post-stroke subjects was highly variable across trials and subjects, it would not be possible to determine common time-varying synergies across trials and subjects.

II. METHODS

A. Subjects

Four right-handed chronic stroke subjects (1 female, 3 male; mean age 68 ± 13 y [min 54 y, max 83 y] with right hemiplegia and 8 healthy right-handed subjects (4 female, 4 male; mean age 67 ± 13 y [min 50, max 87]; one ambidextrous) participated in this study. The healthy subject group was composed of one female and one male subject from a matching 10-year age range for each chronic stroke subject, i.e. there were 8 healthy subjects..

Only right hemiplegic subjects, who were more than 2 years post-stroke, participated in the study. Three of the subjects had only one ischemic stroke (S1: two years post-stroke, S3: six years post-stroke, S4: eighteen years post-stroke). The fourth subject (S2: four years post-stroke) had two consecutive strokes within the same year. Two of the subjects had the ischemic stroke in the internal capsule (S1: posterior limb of the internal capsule, S2: anterior limb of the internal capsule and caudate nucleus). One of the subjects did not provide a medical report (S3), and the other subject (S4) had the stroke in the white matter along the distribution of the left middle cerebral artery. The initial impairment levels of individual subjects were second and third stage for two subjects (S1 and S3, respectively) and fifth stage for the other two subjects (S2 and S4) based on Chedoke McMaster Impairment Inventory/ Stages of Hand. All subjects provided informed written consent and the experimental protocol was approved by Simon Fraser University, Office of Research Ethics.

B. Training

Subjects participated in robot-assisted rehabilitation for 8 weeks, twice a week performing selected exercises based on the degree of impairment and hand functions which the subject desired to recover. The rehabilitation program involved two to three exercises performed using the HandCARE [11] and Haptic Knob [12] robotic systems during a one-hour training session. The amount of training depended on the performance and physical condition of the subject, but each exercise was practiced for at least twenty times.

The exercises with the HandCARE were designated as Isometric (HC1), Sensorimotor (HC2) and Elastic (HC3). In the Isometric exercise (HC1) subjects were instructed to exert isometric force with a specific finger and to relax the other fingers. Their performance scores depended on achieving and briefly maintaining the force within a target window and keeping the force exerted by the other fingers below a specified threshold. Visual feedback of the force exerted by all fingers was provided continuously. HC1 was designed to train independent control of individual fingers. The Sensorimotor exercise (HC2) was similar to the Isometric exercise except that subjects were not given visual feedback. Instead they were provided with tactile feedback in the form of vibration. A small vibrating motor was placed on the finger being trained. When the subject’s force was in the target window the motor was turned on. If the subject exerted too little or too much force the motor was switched off. The exercise could be performed with one or more fingers to train coordination. HC2 was designed to improve the ability to use tactile sensation for controlling finger force and for coordinating finger forces. In the Elastic exercise (HC3), subjects moved all of the fingers in a coordinated fashion against an elastic load created by a torque motor. The objective was to coordinate the applied force and motion so that all of the fingers exerted the same force throughout the movement. Subjects were provided with a visual display related to the force being exerted by each finger. HC3 was designed to improve coordinated actions of the fingers.

The exercises with the Haptic Knob were designated as Open/Close (HK1), Twisting (HK2), which we have also referred to as pronation/supination and Proprioception (HK3). In all exercises, the subjects grasped a disk which was split in two such that the two halves could move apart. The Open/Close exercise (HK1) consisted of two epochs. During the first epoch the Haptic Knob assisted the subject in opening the hand by increasing the separation between the two halves of the disk. During the second epoch, the subject had to close the hand against resistance using visual feedback. HK1 was designed to improve the control of grasp force. The Twisting exercise (HK2) involved rotating the disk between a start and target position while maintaining grip force. HK2 was designed to improve the coordination of grip force and hand rotation. The Proprioception exercise (HK3) required that the subject maintain the grip force within a target window without visual feedback. If the grip force was less than the minimum of the target window the disk rotated in one direction, whereas if the grip force was greater than the maximum of the target window it rotated in the opposite direction. HK3 was designed to improve the ability to process proprioceptive sensation of position and force.

If the subject reached a plateau in performance of an exercise during the 8-week training period, either the level of difficulty of the exercise was increased or a different exercise was substituted. The healthy age-matched subjects had only one training session in which they performed the same exercise program as their age-matched stroke subject had performed in the first training session. Table I summarizes the exercises that each post-stroke subject performed and lists the number of training sessions for each exercise.

Table I: Number of training sessions performed by each post-stroke subjects for each exercise

Subject	S1	S2	S3	S4
Isometric (HC1)	0	0	16	0
Sensorimotor (HC2)	0	12	16	11
Elastic (HC3)	16	4	0	5
Open/Close (HK1)	16	0	0	0
Twisting (HK2)	16	7	16	4
Proprioception (HK3)	0	9	0	12

C. Protocol

Surface electromyography (EMG) was recorded on the first and last day of the robot-assisted rehabilitation from nine hand and forearm muscles, representative of the hand functions being trained. The muscles included extensor carpi radialis brevis (ECR), extensor digitorum communis (EDC), flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS), pronator teres (PT), biceps brachii (BI), first dorsal interosseus (1DI), and abductor digiti minimi (ADM). Electrodes were placed over the belly of the selected muscles, aligned with the direction of the muscle fibers, based on anatomical landmarks [18]. In addition, test movements were performed to ensure that the electrodes were appropriately placed to record activity from the selected muscle and not from neighboring muscles. EMG was recorded using custom active bipolar electrodes (3 mm diameter stainless steel contacts, 13 mm center-to-center distance between contact, bandwidth 20 Hz to 500 Hz), and sampled at 2 kHz.

EMG was recorded during maximal voluntary contraction (MVC) in sixteen different functional movements at the beginning of the session. The maximum value of the mean rectified EMG in a 0.25 s moving window across all movements was determined for each muscle and used subsequently for normalization. EMG for each trial during the training session was processed by first subtracting the mean to remove any DC offset and then rectifying and normalizing. The normalized EMG was low-pass filtered (Butterworth filter; 4 Hz cutoff; zero-phase lag) and re-sampled at 20 Hz using nearest-neighbor interpolation. An example of the unprocessed EMG signal, the rectified-normalized signal, and the low-pass filtered EMG envelope is shown in Fig. 1.

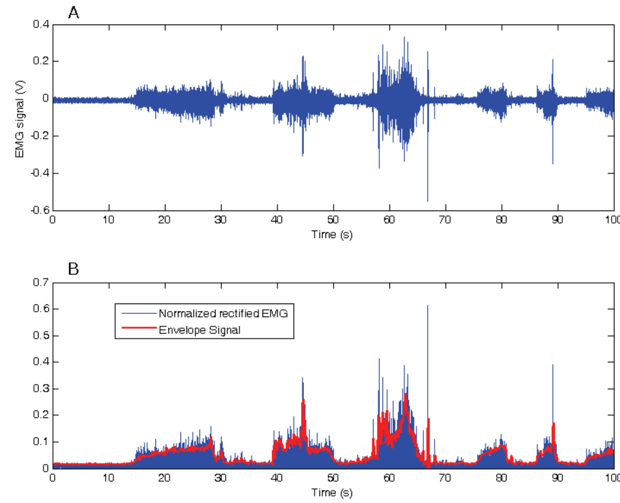

Figure 1: A) An example of an unprocessed EMG signal recorded from the FDS muscle during performance of the Elastic exercise with the HandCARE for a healthy subject. B) The processed zero-mean, rectified, normalized signal (blue) and the low-pass filtered EMG envelope (red) for the signal depicted in A

D. Analysis

Parameters of the synchronous synergies were determined using a non-negative matrix factorization (NMF) algorithm [19] in which the recorded muscle activation vector $\mathbf{m}(t)$ is represented by the following equation:

$$\mathbf{m}(t) = \sum_{i=1}^{N} c_i(t)\mathbf{w}_i \,, \tag{1}$$

where $c_i(t)$ are time-varying coefficients, $\mathbf{w}_i$ are fixed element muscle vectors (synergies) with the elements representing the relative activation of each muscle, and N is the number of synergies. As a measure the goodness of reconstruction, we used the "total variation" [18], defined as the trace of the covariance of the muscle activations, to define a multivariate R^2 measure as follows:

$$R^2 = 1 - \frac{\sum_n \sum_k \left\| \mathbf{m}^n(t_k) - \sum_i c_i^n(t_k)\mathbf{w}_i \right\|^2}{\sum_n \sum_k \left\| \mathbf{m}^n(t_k) - \overline{\mathbf{m}} \right\|^2}, \tag{2}$$

where $\mathbf{m}^n(t_k)$ is the recorded EMG signal vector on trial n at time t_k and $\overline{\mathbf{m}}$ is a vector representing the average EMG level of each muscle across all trials. Thus, R^2 represents the fraction of total variation accounted for by the synergy reconstruction [14].

We ran the NMF algorithm with the number of synergies ranging from 1 to 8 (total number of recorded muscles). We used a method similar to [14] to determine the optimal number of synergies: In [14], the number of synergies was selected based on the dependence of R^2 (the amount of total variation explained) on N. Suppose that N^* synergies are sufficient to explain the variation. Then any additional synergy should only explain variation attributable to noise. Under the assumption that for $N > N^*$ each additional synergy captures an equal amount of noise-generated variation, we expect the R^2 curve to be linear for $N \geq N^*$ [14]. To determine where this occurred we fit a line to R^2 plotted against N for different possible ranges of N, i.e., $N = 1 \ldots 8$, $N = 2 \ldots 8$, $N = 3 \ldots 8$, etc., each time testing whether the mean squared error was $< 5*10^{-4}$. We selected this as being the point where the R^2 curve became linear, using the value of N at the beginning of the line as representing the optimal number of synergies, N^*.

To investigate whether the synergies identified for each exercise were consistent among healthy subjects, the set of optimal synergies was first found to describe the muscle activation patterns for each group of healthy subjects who performed a given exercise, using the procedure described above. The set of optimal synergies was then found for each subject in a group and compared for similarity with the set of optimal synergies for the group. As each muscle synergy is a unit vector, the cosine of the angle between two synergies can be used as a measure of their similarity. For each subject who performed a specific exercise, we defined the average similarity of his/her synergies with the corresponding group synergies as follows:

$$\frac{1}{N^*}\sum_{i=1}^{N^*} \mathbf{w}_i^G \cdot \mathbf{w}_i^j \,, \tag{3}$$

where $\mathbf{w}_i^G$ is the vector of the i^{th} synergy of the group and $\mathbf{w}_i^j$ is the vector of the i^{th} synergy for subject j. N^* is the optimal number of muscle synergies for the group.

III. Results

The optimal number of synergies for each exercise for the healthy subjects is listed in Table II along with R^2 values. The average value of R^2 was 0.92, indicating that it was possible to accurately reconstruct the muscle activation patterns with 3 or 4 synergies. The synergies obtained for individual subjects gave similar results with an average R^2 value of 0.94. When the individual synergies were compared to the group synergies, the average similarity across all exercises was found to be 0.78 (Fig. 2).

Table II: Optimal number of synergies for healthy subjects

Exercise	HC1	HC2	HC3	HK1	HK2	HK3
N^*	4	4	3	3	4	4
R^2	0.92	0.93	0.94	0.93	0.90	0.92

To evaluate changes in the pattern of muscle activation from pre- to post-training in post-stroke subjects, we found the set of optimal synergies for each exercise for each subject before and after the 8 weeks of training. It is possible *i*) that the optimal number of synergies could change and/or *ii*) that the structure of the synergies themselves could change, i.e. the relative amount of activation of each muscle in the synergy could change. To investigate the first possibility *i*), we found the optimal number of synergies pre- and post-training. Table III lists the optimal number of synergies required to reconstruct the EMG for each subject. The average R^2 values for pre- and post-training were 0.91 and 0.92, respectively. In 6 cases, the optimal number of synergies was the same pre- and post-training, in 3 cases the optimal number of synergies increased and in one case the optimal number of synergies decreased. The difference in the number of muscle synergies pre- and post-training was not statistically significant ($p=0.505$, $t(18)=0.46$).

Table III: Optimal number of synergies pre- and post-training for post-stroke subjects

	S1 pre	S1 post	S2 pre	S2 post	S3 pre	S3 post	S4 pre	S4 post
HC1	*	*	*	*	3	3	*	*
HC2	*	*	4	4	3	3	2	3
HC3	4	3	*	*	*	*	*	*
HK1	2	2	*	*	*	*	*	*
HK2	2	3	*	*	3	3	*	*
HK3	*	*	3	4	*	*	3	3

* Subject did not perform this exercise.

To investigate the second possibility *ii*), we found the similarity of the optimal synergies pre- and post-training for each post-stroke subject with respect to those of the group of healthy subjects. In all cases, the average similarity across subjects for each exercise increased from pre- to post-training. The mean value of similarity over all the subjects and exercises was 0.68 (standard error 0.02) pre-training which increased to 0.78 (standard error 0.01) post-training. Thus, on average, the optimal synergies of post-stroke subjects following training were as similar to those of the healthy subject group as those of the individual healthy subjects. The largest increment in average similarity (0.20) was observed for the Open/Close exercise performed with the Haptic Knob (HK1 in Fig. 2). The largest increment in average similarity for exercises performed with the HandCARE (0.15) was observed for the Elastic exercise (HC3 in Fig. 2).

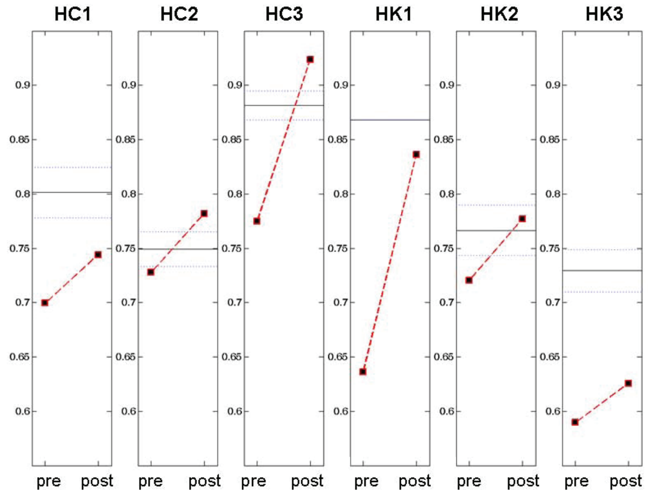

Figure 2: Similarity pre- and post-training for each exercise compared to the healthy subject group. The mean similarity index for the individual healthy subjects is shown by the solid horizontal line. The dotted horizontal lines represent the standard error of the mean for the individual healthy subjects. The filled squares connected by dashed red lines show the mean similarity index pre- and post-training for the post-stroke subjects who performed each exercise (Table I).

An example of the type of change in the optimal muscle synergies observed from pre- to post-training, is shown for one post-stroke subject (S1) in Fig. 3. The comparative muscle synergies obtained from the group of healthy subjects performing the same exercise is shown in the first column. The robot-assisted training had two effects. First, the independent control of individual muscles appears to improve since superfluous activity in several muscles (relative to the healthy group) is reduced post-training, e.g. BI and PT in Synergy 1 and BI in Synergy 2. Second, activity in some of the primary muscles of the synergy increases post-training, e.g. EDC in Synergy 1 and FCU in Synergy 2).

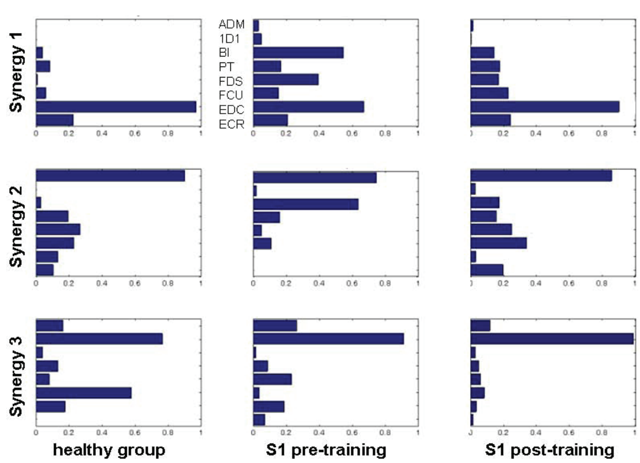

Figure 3: Comparison of the 3 optimal synergies for exercise HC3 for the healthy group with those of subject S1 pre- and post-training. Synergies 1 and 2, in particular, show changes in the relative activation of certain muscles that result in synergies that better resemble those of the healthy group post-training than pre-training.

IV. CONCLUSIONS

We have previously reported the benefits of training with the Haptic Knob on improvements in hand function in post-stroke subjects [20]. In this study, we have also been able to demonstrate that patterns of muscle activation for arm and finger muscles more closely resemble those of age-matched healthy subjects following training than before training. Given that the post-stroke subjects had experienced their stroke more than 2 years prior to participation in the study, these results suggest that neural plasticity in the brain can be exploited long after the stroke has occurred to modify muscle activation patterns. Furthermore, this plasticity exists even in elderly individuals. Although our study does not permit us to state definitively whether the observed changes in the structure of the optimal muscle synergies was primarily due to a relative increase in excitation or increase in inhibition of different muscle pairs, there is evidence that both occur.

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REFERENCES

[1] J.G. Colebatch and S.C. Gandevia, "The distribution of muscular weakness in upper motor neuron lesions affecting the arm." *Brain*, vol. 112, pp. 749-763, 1989.

[2] S. Brunnström, *Movement Therapy in Hemiplegia. A Neurophysiological Approach*., New York: Harper and Row, 1970.

[3] D.G. Kamper and W.Z. Rymer, "Quantitative features of the stretch response of extrinsic finger muscles in hemiparetic stroke." *Muscle Nerve*, vol. 23, pp. 954-961, 2000.

[4] L. Masia, H. Krebs, P. Cappa, and N. Hogan, "Design, characterization,and impedance limits of a hand robot," Proc. of the IEEE Int. Conf. on Robotic Rehabilitation (ICORR), 2007.

[5] T. Nef, M. Mihelj, G. Colombo, and R. Riener, "ARMIN – robot for rehabilitation of the upper extremities," Proc. of the IEEE International Conference on Robotics and Automation, pp. 3152–3157, 2006.

[6] C. Takahashi, L. Der-Yeghiaian, V. Le, and S. Cramer, "A robotic device for hand motor therapy after stroke," Proceedings of the 9th IEEE International Conference on Rehabilitation Robotics (ICORR), pp. 17–20, 2005.

[7] M. Bouzit, G. Burdea, G. Popescu, and R. Boian, "The Rutgers Master II: New design force-feedback glove," IEEE/ASME Transactions on Mechatronics, pp. 256–263, 2002.

[8] H. Kawasaki, S. Ito, Y. Nishimoto, and H. Kimura, "Hand rehabilitation support system based on self-motion-control," TExCRA, pp. 55–56, 2004.

[9] L. Yanlin, J. Murayama, K. Akahane, S. Hasegawa, and M. Sato, "Development of new force feedback interface for two-handed 6dof manipulation –SPIDAR-G and G system," ICAT, 2003.

[10] U. Mali and M. Munih, "HIFE-haptic interface for finger exercise," IEEE/ASME Transactions on Mechatronics, vol. 11, pp. 93–102, 2006

[11] L. Dovat, et al., "HandCARE: a Cable-Actuated REhabilitation system to train hand function after stroke." *IEEE Trans. Neural Syst. Rehabil. Eng*., vol. 16, pp. 582-591, 2008.

[12] O. Lambercy, et al., “A haptic knob for rehabilitation of hand function.” *IEEE Trans. Neural Syst. Rehabil.*, vol. 15, pp. 356-366, 2007.
[13] A. d'Avella and E. Bizzi, "Shared and specific muscle synergies in natural motor behaviors." *PNAS*, vol. 102, pp. 3076-3081, 2005.
[14] A. d'Avella, A. Portone, L. Fernandez, and F. Lacquaniti, "Control of fast-reaching movements by muscle synergy combinations." *J. Neurosci*., vol. 26, pp.7791-7810, 2006.
[15] C.A. Trombly and M.V. Radomski (2002). *Occupational Therapy for Physical Dysfunction.* Philadelphia: Lippincott Williams and Wilkins, 2002.
[16] L. Dipietro, et al.,"Changing motor synergies in chronic stroke." *J. Neurophysiol*., vol. 98, pp. 757-768, 2007.
[17] A. d'Avella, P. Saltiel, and E. Bizzi, "Combinations of muscle synergies in the construction of a natural motor behavior." *Nat. Neurosci.*, vol. 6, pp. 300-308, 2003.
[18] A.O. Perotto, *Anatomical Guide for the Electromyographer*. Springfield: Charles C. Thomas, 2005.
[19] D.D. Lee and H.S. Seung, “Algorithms for non-negative matrix factorization.” *Adv. Neural Info. Proc. Syst*, vol. 13, pp. 556-562, 2001.
[20] O. Lambercy, et al., “Exercises for rehabilitation and assessment of hand motor function with the Haptic Knob.” *I-CREATE*, 2009.