Evaluation of a Pose-Shared Synergy-Based Isometric Model for Hand Force Estimation: Towards Myocontrol

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Abstract In this work the authors investigated whether the muscle synergies concept could improve the isometric hand force estimation. Electromyographic (EMG) activity from 9 arm muscles and hand forces applied at the Light-Exos Exoskeleton end-effector were recorded during isometric contractions in several workspace points lying on the parasagittal plane crossing the shoulder joint. The muscle synergies were extracted in two different ways according to the statements that the muscle primitives are '*Arm Pose Related*' or '*Arm Pose Shared*'. From the pre-processed EMG signals the authors then estimated the hand forces using three methods. The results showed that the muscle synergy concept improves the isometric force estimation paving the way for a synergy-based myoelectric control.

1 Introduction

Several studies have supported the existence of muscle synergies as neural control strategy employed by the central nervous system for motor coordination in static and dynamic motor tasks [1, 2]. Berger and d'Avella [1] first have proven that muscle synergies computed at a defined arm pose can be used to estimate target forces in isometric planar reaching tasks, showing that human subjects were able to perform

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reaching tasks after switching from force-control (using a force sensor) to synergy-control (based on the EMG signals from 13 arm and shoulder muscles).

In this preliminary study, the authors extend this analysis to different arm poses in the sagittal plane, investigating whether muscle synergies computed from muscle activations could effectively used for a better isometric hand force estimation. This study in particular investigates whether synergies should be interpreted as '*Pose-Related*' or '*Pose-Shared*' muscle primitives of human motor control. To this aim, the authors compare two different approaches for synergy extraction and compare the hand force estimation obtained with 3 different methods, to understand whether and how muscle synergies can be used to detect the human's isometric force.

2 Materials and Methods

2.1 Procedures

One healthy subject participated in the study, repeating two independent measurement trials in two different days. The subject put a wearable robotic exoskeleton on his right arm, the Light-Exos [3], and was asked to grasp a force sensorized handle at the end effector (EE), whose position in the space was set at 13 pre-defined points in the parasagittal plane crossing the shoulder joint, while supporting his own arm weight. For each point the subject was asked to perform two isometric contractions generating a force (reference value was set to 15 N) along each of the 8 directions within the sagittal plane, while forces were recorded together with EMG activations. Instructions on the direction of force were provided within a virtual environment using a head mounted display to show the direction cues.

2.2 EMG Collection and Pre-processing

The sEMG signals of 9 arm and shoulder muscles (short and long heads of biceps, brachioradial, lateral and long heads of triceps, anterior and posterior heads of deltoid, teres major and infraspinatus) were recorded using pre-gelled electrodes in bipolar configuration, sampled and acquired at 1200 Hz by using a g.USBamp amplifier (www.gtec.at). The EMG signals were pre-processed with the following steps to compute the *muscle activations*: 20–500 Hz band-pass filtering; signal rectification; 2 Hz low pass filtering; tonic component removal; normalization by the standard deviation.

2.3 Synergies Extraction

Muscle synergies were identified by using the non-negative matrix factorization (NMF) [4] from EMG patterns collected during the contraction phases: $m = Wc +$

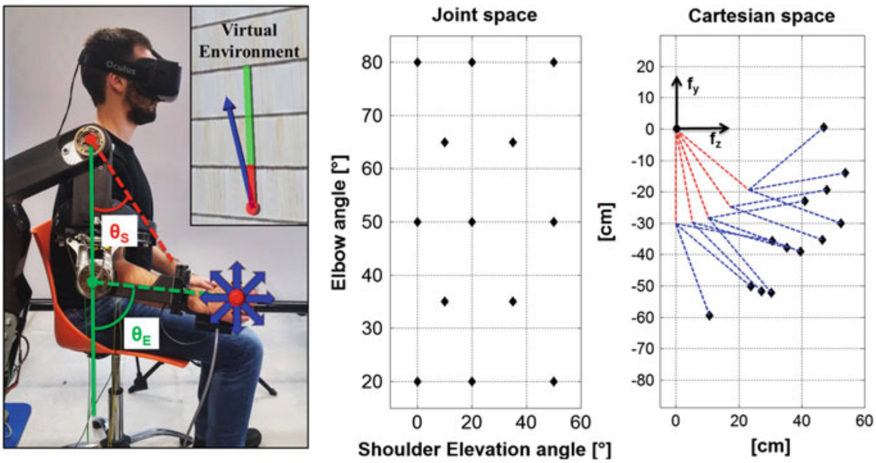

Fig. 1 *Left* Acquisition setup. *Right* 13 arm poses

e_m, where W is the synergy matrix, m is the muscle activation vector, c is the synergy activation vector and e_m is the vector of the muscle activation residuals.

The muscle synergies were extracted with two different methods. In the first one, '*Pose-Shared synergies*' were extracted by computing NMF on the entire dataset acquired during the acquisition. In the second method '*Pose-Related synergies*' were composed through two steps: (1) NMF was independently executed on dataset acquired at each pose, then synergies were extracted when the coefficient of determination R^2 reached a value higher than 0.90; (2) all the extracted synergies were clustered using a K-means algorithm (distance: cosine), then the general '*Pose-Related synergies*' matrix was composed by grouping the cluster centroids as columns. The first method and the second step of the second one were repeated for a number of synergies ranging from 2 to 9. From the comparison of the R^2 obtained with the two methods in Fig. 2 shows, it is evident that '*Pose-Shared synergies*'can better reconstruct the muscle activations than '*Pose-Related synergies*'. So '*Pose-Shared*' synergies were used in the force estimation following step.

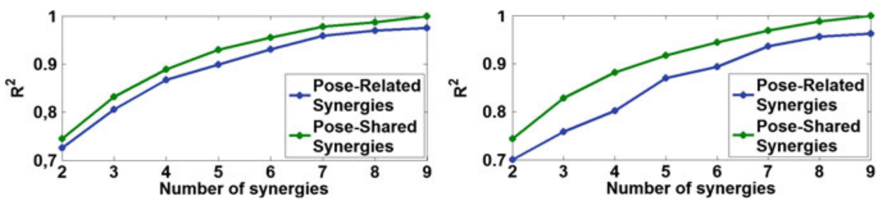

Fig. 2 R^2 comparison in two different acquisitions

2.4 Hand Force Estimation

The hand isometric force estimation was performed by three different methods:

(1) $\boldsymbol{f} = \boldsymbol{H_p m}$, (**M2F**): the force components ($\boldsymbol{f}$) are assumed as linear functions of the entire muscle activations m dataset ([1]),
(2) $\boldsymbol{f} = \boldsymbol{H_p W W^{+} m}$, (**pM2F**): the force components ($\boldsymbol{f}$) are assumed as linear function of the projection of muscle activations m into the synergy space ([1]),
(3) $\boldsymbol{f} = \boldsymbol{\hat{H}_p c}$, (**C2F**): the force components ($\boldsymbol{f}$) are assumed as linear function of the synergy activations c (originally proposed here).

where $f \in \Re^2$, W and W^{+} are the synergy matrix (with 5 synergies) and its pseudo-inverse. H_p and $\hat{H}_p$ are pose-dependent and were estimated using multiple linear regressions of each applied force component with the *muscle activations* and the *synergy activations*, respectively.

3 Results and Discussion

The three estimation methods were compared evaluating the validation root mean square value (E_{RMS}) of the module of error vector between the measured and the estimated force. For each arm pose, a 2-fold cross-validation procedure was iterated 2^7 times for all training sets, composed of all possible combination of each contraction along the 8 directions. For each point p and for each training/validation pair set i, the validation E_{RMS} were computed for each method obtaining the following two differences:

$$\Delta^{(pi)}_{M2F-C2F} = E^{M2F(pi)}_{RMS} - E^{C2F(pi)}_{RMS} \tag{1}$$

$$\Delta^{(pi)}_{pM2F-C2F} = E^{pM2F(pi)}_{RMS} - E^{C2F(pi)}_{RMS} \tag{2}$$

Table 1 reports the averaged values across both the training/validation sets i and the arm pose p.

It appears how qualitatively the third force estimation method performs better than the first and second ones, since the average error differences $\Delta_{M2F-C2F}$ and $\Delta_{pM2F-C2F}$ are always positive. This preliminary evidence is very promising, since it shows how the interpretation of hand force generation in terms of muscle synergies,

Table 1 Method comparison

	Validation $\Delta_{M2F-C2F}$	Validation $\Delta_{pM2F-C2F}$
Acquisition 1	0.36 ± 0.45 N	0.78 ± 1.12 N
Acquisition 2	0.33 ± 0.30 N	1.13 ± 0.62 N

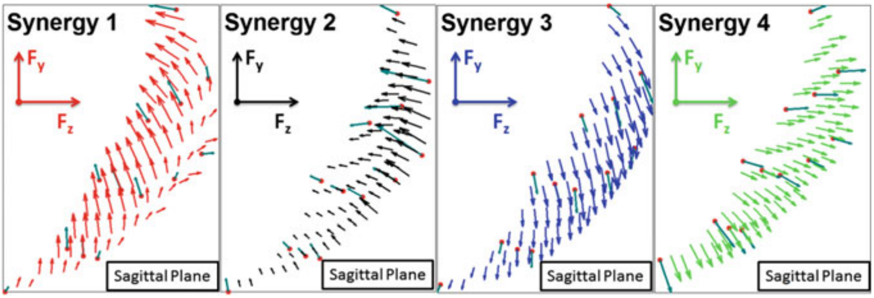

Fig. 3 Sinergy-Force Maps. *Force arrows* are computed using estimated the $\hat{H}_p$ (in *gray*) and interpolated $\hat{H}_p^i$ (*colored*)

used in method 3-C2F, can improve the estimation of the human's hand isometric force over different poses.

In order to provide a graphical interpretation of this results, the 13 matrices $\hat{H}_p$ (computed with 4 synergies) were linearly interpolated in the joint space. Figure 3 shows how the matrices $\hat{H}_p$ project the synergy activations into the planar YZ force space for each pose p. The regularity of the derived plots is interesting, as it allows to hypothesize the usage of this approach for proportional myoelectric control of exoskeleton in rehabilitation tasks.

4 Conclusion

In this paper, the authors investigated the role of muscle synergies in isometric hand force estimation in different arm postures. Preliminary analysis showed that the 'Pose-Shared' synergies are able to explain the variation in muscle patterns better than the 'Pose-Related' synergies, but more accurate experiments are needed. The comparison among three different isometric hand force estimation methods proved that muscle primitives could be useful to detect the motion intention paving the way for synergy-based myocontrol.

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