Synergy-Based Myocontrol of a Two Degree of Freedom Robotic Arm in Children with Dystonia

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Abstract We tested the ability of a synergy-based myocontrol scheme to achieve simultaneous, continuous control of two degrees of freedom (DOFs) of a robotic arm that reproduces the child's movement (or intention of movement), using muscle synergies extracted from muscles recorded during both isometric contractions and unconstrained flexion-extension movements of elbow and shoulder joints in the horizontal plane. The aim of the current work was to validate the feasibility and the efficacy of the synergy-based approach for multi-DOF robotic control in children with dystonia, compared to the simple muscle-pair method typically used in commercial applications. The proposed synergy-based scheme showed a better performance compared to the traditional muscle-pair approach, both in dynamic and isometric conditions. The current study represents a crucial successful first step toward synergy-based working solutions for children with dystonia.

1 Introduction

In the most severe cases, as for children with tetraplegic or dyskinetic cerebral palsy (CP), children with dystonia have very limited ability of movement and communication. For such children, assistive technologies have the potential to provide

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mobility, manipulation, and functional communication. Myoelectric control represents a possible solution that children with CP can use to control assistive devices. However, multi-muscle myocontrol still represents an unsolved problem due to the high-dimensionality of control signals and the simultaneous control of multiple DOFs. A promising solution is a myoelectric control approach based on the synergy model [1, 2]. Indeed, muscle synergies extracted from multiple electromyographic (EMG) channels represent underlying muscle coordination principles [3], making possible to describe a variety of EMG patterns as a combination of such muscle modules. A recent study [4] showed that upper limb muscle synergies in dystonia are able to capture fixed patterns of muscle activity, making them appropriate signals for myoelectric control in children with dystonia. Based on this promising finding, the aim of the current work was to validate the feasibility and the efficacy of the synergy-based approach for multi-DOF robotic control in children with dystonia, compared to the simple muscle-pair method typically used in commercial applications.

2 Materials and Methods

2.1 Participants

Participants consisted of 5 children with secondary dystonia (1 girl; ages 11–21 years, mean 16.6 + 3.6 years; severity of the arm tested (Barry-Albright Dystonia Scale) 1–3). 4 subjects participated in the Dynamic Protocol, and 4 subjects participated in the Isometric Protocol.

2.2 Experimental Apparatus

Surface EMG was acquired using the DataLOG MWX8 device (Biometrics Ltd; 1000 Hz sampling frequency; 15–450 Hz band-pass): Brachioradialis (BRACH), Anconeus (ANC), Biceps Brachii (BIC), Triceps Brachii (TRIC), Anterior Deltoid (AD), Lateral Deltoid (LD), Posterior Deltoid (PD), and Supraspinatus (SS). The algorithm computed online the torque signals to drive two DOFs of a robotic arm, the Phantom® Premium 1.0 (SensAble™), to mimic flexion-extension movements in the horizontal plane of the shoulder (DOF 2) and the elbow (DOF 1) joints. The robot returned information from the encoders and the 3-D position of the end-effector (1000 Hz). In the Dynamic Protocol, a 6-D motion-tracking system (Flock of Birds®, Ascension 100 Hz sampling frequency) was used to track the subject's elbow and shoulder flexion-extension angles in the horizontal plane (Fig. 1).

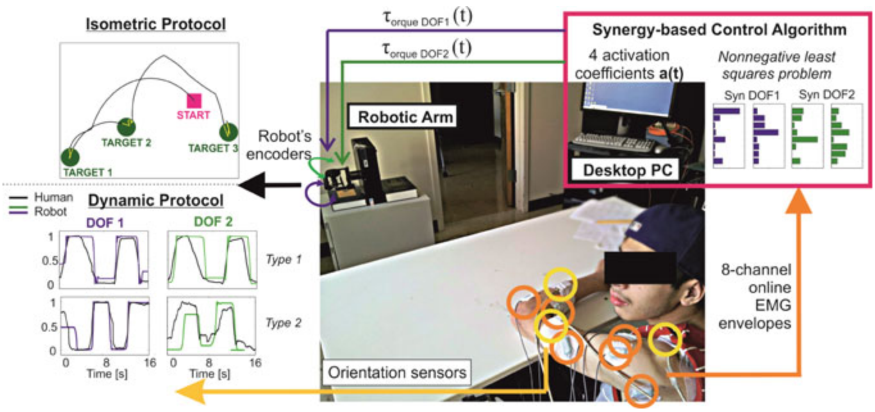

Fig. 1 Given the online EMGs and the subject-specific synergies (extracted from the calibration phase), the control algorithm computes the activation coefficients that are used to derive the torque signals to drive the 2 DOFs of the robotic arm. Dynamic Protocol: the robot's (encoders) and the subject's (orientation sensors) angles are compared. Isometric Protocol: the subject, in front of a monitor, is instructed to reach 3 targets, through control of a cursor that tracks online the 2D position of the robot's end-effector

2.3 *Control Algorithm and Experimental Protocols*

This study leverages a synergy-based myocontrol scheme developed by our group [5] to achieve control of 2 DOFs of a robotic arm, using muscle activity recorded during both unconstrained flexion-extension movements of elbow and shoulder joints in the horizontal plane (Dynamic Protocol) and isometric contractions (Isometric Protocol).

Both protocols consisted of three phases. The first step was a calibration phase, in which the subject was asked to perform movements (or isometric contractions) of the two DOFs separately. A DOF-wise Nonnegative Matrix Factorization (NMF) was applied to the single-DOF EMG signals recorded during the calibration phase to extract two synergies for each DOF separately, and to associate each synergy to positive or negative directions of that specific DOF. The calibration was followed by a synergy-based control phase, during which the subject achieved online simultaneous control of the robot's DOFs. Given the online nonlinear envelopes [6] of the EMG signals and the subject-specific synergies, the algorithm extracted, by solving a nonnegative least-squares constraint problem, the activation signals that were used for online simultaneous torque-based control of the two DOFs. For the Dynamic Protocol, each participant achieved two types of double-DOF movements: in the first type (Type1), DOF 1 and DOF 2 were first extended and then flexed simultaneously; in the second type (Type2), the two DOFs were articulated in opposite directions. For the Isometric Protocol, the participant was seated in front of a monitor displaying three targets and a cursor that tracked online the 2D position of the robot's end-effector. The subject was instructed to reach each target as fast as possible and to pause with the cursor within the target. The task was accomplished when the subject reached all three targets, regardless from the order, within a 45-s time interval. Each subject performed 3 trials. A third control phase implemented the traditional muscle-pair approach, in which each DOF was controlled by the difference between the two EMG signals most relevant for each DOF (DOF 1: BIC and TRIC; DOF 2: AD and PD).

2.4 Performance Analysis

For the Dynamic Protocol, the performance of the control algorithm was assessed by computing Root-mean-square Error (RMSE) and Pearson's Correlation coefficient (r) between the subject's and the robot's angles (DOF 1 and DOF 2 separately). For the Isometric Protocol, the performance was assessed through the average speed (V) and the Index of Performance (IP) for all targets [5].

3 Results

For the Dynamic Protocol, repeated measures ANOVA reported significant differences between the synergy-based and the muscle-pair approaches both for RMSE ($p = 0.05$) and r ($p = 0.05$). In particular, the synergy-based approach showed decreased RMSE values (Synergy: 0.30 ± 0.11; Muscle-pair: 0.37 ± 0.16) and higher correlation between the subject's and the robot's joint angles compared to the muscle-pair approach (Synergy: 0.74 ± 0.55; Muscle-pair: 0.55 ± 0.39). For the Isometric Protocol, including all subjects, a larger number of targets was reached when using the synergy-based control interface, compared to the muscle-pair controller (Synergy-based: targets reached: 29, targets missed: 7; Muscle-pair: targets reached: 25, targets missed: 11). The average speed at which subjects reached targets using the synergy-based approach was significantly increased ($p = 0.03$) compared to the muscle-pair method (Synergy: 22.69 ± 9.21 cm/s; Muscle-pair: 13.57 ± 5.45 cm/s). No significant between-approach difference was reported for IP ($p = 0.13$).

4 Discussion and Future Work

This is the first study that successfully validates synergy-based, online, simultaneous myoelectric control of two DOFs of a robotic arm in children with dystonia. All patients were able to intuitively control the myoelectric interface. The proposed control scheme was shown to provide better performance compared to the traditional muscle-pair approach. The current study represents a crucial successful first step toward user-friendly application of synergy-based myocontrol of assistive robotic devices in different scenarios. Indeed, the dynamic scheme could be thought as a useful approach to control wearable esoskeletons that may assist patients whose symptoms still allow residual, yet considerably variable movements. To this aim, future work should address the issue of whether the presence of an esoskeleton affects muscle synergies. On the other hand, the isometric scheme is a promising approach that can be used for the control of external devices by severe patients, for which dystonia prevents any sort of functional movement. Future work should increase the number of DOFs, also dealing with possible cross-talk issues.

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References

1. N. Jiang, I. Vujaklija, H. Rehbaum, B. Graimann, D. Farina, Is accurate mapping of EMG signals on kinematics needed for precise online myoelectric control? IEEE Trans. Neural Syst. Rehabil. **22**(3), 549–558 (2014)
2. D.J. Berger, A. d'Avella, Effective force control by muscle synergies. Front. Comput. Neurosci. **8**(46) (2014)
3. L.H. Ting, S.A. Chvatal, *Decomposing Muscle Activity in Motor Tasks in Motor Control, Theories, Experiments and Applications* (Oxford University Press, New York, 2010), pp. 102–138
4. F. Lunardini, C. Casellato, M. Bertucco, T.D. Sanger, A. Pedrocchi, Muscle synergies in children with dystonia capture "healthy" patterns regardless the altered motor performance, in *Conference Proceedings of IEEE Engineering in Medicine and Biology* Society 2099–2102 (2015)
5. F. Lunardini, C. Casellato, A. d'Avella, T.D. Sanger, A. Pedrocchi, Robustness and reliability of synergy-based myocontrol of a multiple degree of freedom robotic arm. IEEE Trans. Neural Syst. Rehabil. Eng. (2015)
6. T.D. Sanger, Bayesian filtering of myoelectric signals. J. Neurophysiol. **97**(2), 1839–1845 (2007)