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Vibro-tactile EMG-based biofeedback induces changes of muscle activity patterns in childhood dystonia

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Abstract— **Childhood dystonia has been associated with injury to the basal ganglia, however there is evidence suggesting the involvement of sensory cortex, cerebellum and brainstem. Even though dystonia is considered a movement disorder, recent studies have shown dysfunctional sensorimotor integration that further contributes to the dystonic symptoms. Such aberrant circuitry may prevent children with dystonia from acquiring new motor tasks. The use of EMG-based biofeedback has been proposed as a promising technique to augment sensory information and consequently improve motor function. The aim of this study is to test the effects of a newly designed vibrotactile EMG-based biofeedback device to induce changes of muscle patterns in children with dystonia during a continuous figure-eight task. We show a change in muscle activation task components when participants receive the biofeedback while performing the task. Those changes suggest new neuromotor solutions in the framework of "motor exploration" as a strategy in the early phases of motor learning.**

I. Introduction

Childhood dystonia is defined as a "movement disorder in which involuntary sustained or intermittent muscle contractions cause twisting and repetitive movements, abnormal postures, or both" [1]. Dystonia has been associated with injury of the cortico-striatal-thalamo-cortical motor circuits, suggesting an abnormal sensorimotor integration and control of movements [2]. The anomalous or absent modulation of afferent inputs and intra-cortical inhibition could result in sensory deficits [3] and inability to suppress unwanted components of muscle activity [4], which may partly contribute to the genesis of dystonic symptoms. Aberrant sensorimotor processing and sensory deficits may lead to dysfunctional neural plasticity that may prevent children with dystonia from learning new motor tasks.

Biofeedback (BF) is a subtype of augmented feedback in which information on physiological processes is delivered to an individual by a trainer or a display [5]. BF is thought to assist the person to enhance awareness of these processes and increase volitional control. BF represents a supplemental afference to the CNS that can supplement or substitute for the sensorimotor loop, thus resulting in improved voluntary motor control. Electromyography (EMG)-based biofeedback has been largely used in neurorehabilitation and physical therapy, as it can facilitate the learning of fine control of muscle activity [6]. The effects of EMG-based BF have shown encouraging results in children with dystonia to improve motor functions [7]. Particular attention has been recently paid to the tactile-vibrating modality of BF information since it is able to direct attention to specific areas of the body [8]. In our lab, we have designed and built a battery-powered wearable and portable EMG biofeedback device that alerts the person wearing the device of muscle activity by smooth changes in the speed of a silent vibration motor. It has been shown to provide motor function improvement in children with dyskinetic cerebral palsy (CP) [8]. However, the driving mechanism of EMG-based BF to produce changes in motor functions, and potential muscle activity adaptations in childhood dystonia has not yet been fully investigated yet.

We have recently developed an innovative and practical method to untangle and quantify the task-relevant and task-irrelevant components of muscle activity [4]. It was demonstrated that children with dystonia are characterized by increased task-irrelevant components of muscle activity, which is in accordance with previous studies suggesting the inability to suppress unwanted muscle and motor program components. In this respect, this technique can be used to investigate the impact of EMG-based BF on muscle task components in childhood dystonia.

The goal of our study was to test whether children with dystonia were able to voluntary modulate their muscle patterns with a real-time EMG-based BF signal into the sensorimotor loop during a figure-eight writing task.

II. Methods

A. Participants

The participants of the current study are from the same sample recruited for our previous study [4] in which we measured the muscle task components without using the vibro-tactile EMG-based BF. Five main criteria were defined for the inclusion of participants in this study: I) primary or secondary dystonia; II) pediatric age (8-21 years); III) upper limb control impairment compatible with the writing task execution; IV) no cognitive impairment hampering the understanding of instructions; V) no deep brain stimulation (DBS). Participants consisted of 7 children with dystonia (12.6 ± 4.7 years) recruited from the Children's Hospital Los Angeles and diagnosed by a pediatric neurologist and of a control group of 9 neurologically healthy children (15.8 ± 4 years). The University of Southern California Institutional Review Board approved the study. All parents gave informed

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written consent for participation and authorization for use of protected health information, and all children gave written assent.

B. Set-up and protocol

The study protocol consisted in a writing task. Subjects were asked to outline with a pen a figure "8" at their natural speed on a tablet (9.7-inch screen size, 1024-by-768-pixel resolution, iPad, Apple®; sampling rate: 60 Hz) positioned on the table, following a thin trace on the screen for thirty repetitions divided into three blocks of ten movements each. They were asked to execute the task with their preferred or dominant hand for children with dystonia, and healthy children respectively. Subjects were given an initial up to 20 trials of practice to familiarize with the device. Each subject performed the task in three conditions: without biofeedback (BF), with BF on a proximal arm muscle, and with BF on a distal arm muscle (NBF, PBF and DBF respectively). BF target muscles were chosen for each subject among the most active muscles or the ones mostly involved in the movement in each of the two body segments. MVC values for the target muscles were recorded. The EMG-based biofeedback device used for the study has been developed in our lab and previously reported. It consists of a surface EMG sensor and amplifier, microcontroller-based nonlinear signal processing, and vibration motor (C1234B016F, Jinlong Machinery, Zhejiang, China, 80-150 Hz vibration) to provide feedback of muscle activity. Children were asked to reduce the vibration strength of the motor by reducing the activation of the target muscle as much as possible. Eight surface EMG electrodes (SX230 from Biometrics Ltd, Newport, UK; sampling rate: 1000 Hz) were placed on 8 muscles of the upper limb (Flexor Carpi Ulnaris (FCU), Extensor Carpi Radialis (ECR), Biceps (BIC), Triceps (TRIC), Anterior Deltoid (AD), Middle Deltoid (or Lateral Deltoid) (LD), Posterior Deltoid (PD) and Supraspinatus (SS)) of the subjects, with an inter-electrode distance of 20 mm. In order to optimize the recording of EMG data, the skin over the muscles and the surface of the electrodes were prepared and cleaned with isopropyl alcohol pads to reduce the impedance at the skin-electrode interface. The 2D coordinates of the stylus pen tip during the writing task on the tablet were recorded. A specific application had previously been developed in Cocoa (Apple®) to display the task interface and to record the trajectory (2D coordinates) of the pen tip. All these measurements were integrated in the acquisition system (Figure 1). Subjects were seated on an armless chair at a distance allowing them to reach the furthest point on the tablet screen with an elbow extension of 90% of the maximum. In order to avoid movements of the trunk, each subject was fastened to the chair back with a Velcro® belt.

C. Data Analysis

Data analyses were executed with the software Matlab (Mathworks®). Statistical analysis was performed using RStudio® (RStudio Inc.©, Boston, MA, USA). Representative parameters from kinematic and EMG data were computed.

Joint EMG-kinematic analysis

Before performing the spectral analysis, each EMG signal was processed with a band-pass Butterworth filter (5th order, 5-400 Hz), rectification, and a stop-band Butterworth filter (5th order, 60 Hz).

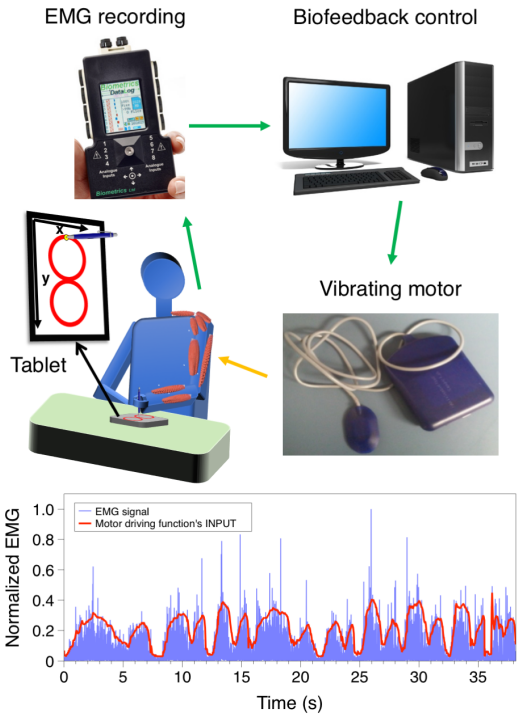

Figure 1. The figure shows the experimental set-up.

EMG signals were then normalized to the maximum activation during the movement, resulting in signals ranging from 0 to 1. A nonlinear recursive filter based on Bayesian estimation was applied (*Filt*) [9]. In order to detect the frequency features related to the motor outcome on the EMG signals, spectral analysis was applied to kinematic (Ytablet and Xtablet) and EMG data (normalized Bayesian filtering outputs) [4]. Each kinematic and EMG signal was pre-processed as follows: I) the sequence was divided into the 10 single figure-eight movements; II) each movement was re-sampled to equalize the duration of the figure-eight movements between all subjects; III) re-sampled movements were re-assembled in order to rebuild the sequence; IV) the signal was linearly de-trended; V) Fourier Transform (FT) of the re-sampled sequence was computed. We then computed the Power Spectral Density (PSD) based on the FT coefficients for kinematic and EMG signals (Figure 2). The PSD analysis allows to calculate the EMG components related to the task. Because the task consists of cyclic movements in the shape of a figure 8, only frequency components with a period T (the time to complete the figure 8) or T/2 (the time to execute the horizontal/vertical component of the figure 8) are related to the task. All other frequencies are task-unrelated. The ratio of these components and the full spectrum energy was regarded as an index of muscle activity related to the task and appointed as "*task-correlation index*" (*TCI*). The *TCI* was computed for each sequence of ten single figure-eight movements and averaged over the three sequences performed. In order to quantify the muscle activity, the root mean square (*RMS*) value of the EMG bayesian envelope was also computed.

Touchscreen analysis

The *error* of the figure-eight trace on the tablet was computed as the root mean square error between the actual pen trajectory and the figure-eight trace displayed on the tablet for each movement separately.

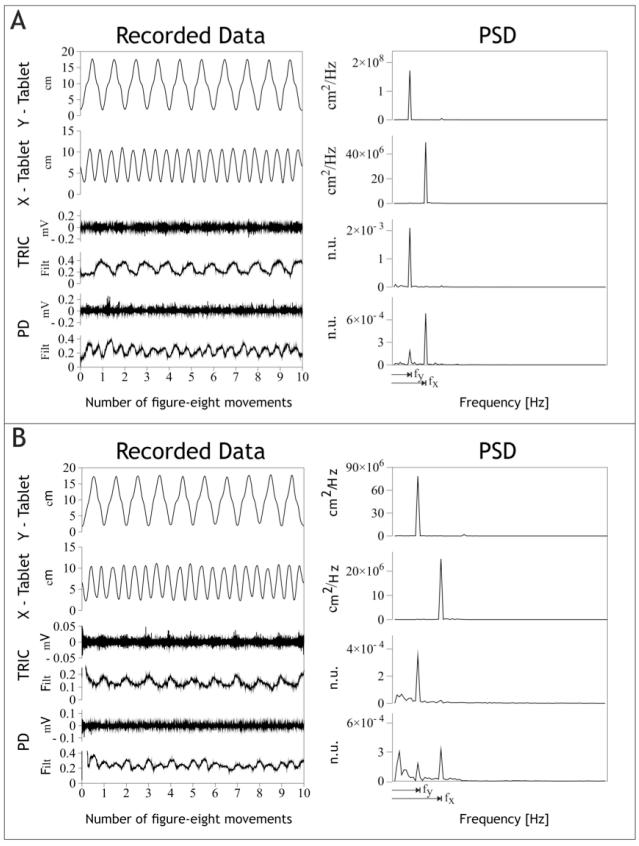

Figure 2. EMG-kinematics spectral analysis: A) healthy child; B) child with dystonia.

The value was then averaged over all movements. The *speed* was calculated for each figure-eight movement and then averaged over the thirty single movements. Since motor speed and accuracy interact, to quantify motor performance, it is important to measure them together [10]. Therefore, we examined motor skill during the writing task by computing the ratio between error and speed (*Err/Speed*) for each movement separately, and we averaged it over the thirty movements. The intrasubject spatial variability of the stylus pen was estimated as the average standard deviation of the trajectories after time alignment. In order to do that, data were shifted in the frequency domain. The *spatial variability* (*VarS*) was computed for the tablet trajectories and the intra-subject *temporal variability* (*VarT*) was quantified as the standard deviation among the durations of each movement.

Statistical analysis

To test the difference on the dependent variables between groups and biofeedback conditions we performed a linear mixed effects analysis (lmer, R lme4 package, version 1.1-7). As fixed effects, we entered BF (3 levels: NBF, PBF, DBF) and Group (2 levels: Dystonia and Control) into the model. As random effects, we had intercepts for subjects, as well as by-subject random slopes for the effect of BF. We compared the model including all the factors (Full) against a reduced model without the effect in question (Null), for each dependent variable and for each factor. For all comparisons, P values and Akaike's information criterion values (AIC) were obtained by likelihood ratio tests of the Full model with each Null model [11]. If the factor in question significantly affects the dependent variable, then the comparison will report a significant P value (<0.05) and an AIC value lower for the Full model (AIC-Full).

III. Results

PBF targeted muscles were AD, PD LD and SS for eight, one, two and four participants, respectively. DBF targeted muscles were ECR and FCU for thirteen and three participants respectively. One participant with dystonia was tested only for DBF. The likelihood ratio test reported a significant effect on *TCI* for Group (AIC-Full =-472.96; AIC-Null=-469.68; P<0.05) and BF (AIC-Full=-502.27; AIC-Null=-469.68; P<0.001) with no interactions. On average, the Dystonia group had lower *TCI* (*M*=0.300, *SEM*=0.025) with respect to Controls (*M*=0.384, *SEM*=0.022). Also, the model predicted a decreased of TCI with PBF (*M*=0.319, *SEM*=0.018) and DBF (*M*=0.316, *SEM*=0.021) with respect to NBF (*M*=0.389, *SEM*=0.019), meaning that TCI decreased more significantly when participants were asked to suppress muscles with vibratory biofeedback (Figure 3). To test the effect of BF on *TCI* for all the upper arm muscles we performed the linear mixed effects analysis by removing the BF targeted muscles from the model. Interestingly, the likelihood ratio test shows comparable significant effect on *TCI* for Group (AIC-Full=-428.76; AIC-Null=-424.61; P< 0.05) and BF (AIC-Full=-468.64; AIC-Null=-424.61; P< 0.001) when BF targeted muscle was excluded in the model (Figure 3). The effect size of BF intervention on TCI for Dystonia group was on average -1.69, -3.08, -3.85, -3.52, -4.35, -2.94, -4.79 and -3.00 for muscles FCU, ECR, BIC, TRIC, AD, LD, PD and SS respectively. For Control group the effect size was on average -4.62, -2.51, -3.41, -2.12, -4.51, -1.75 -4.50 and -2.45 for muscles FCU, ECR, BIC, TRIC, AD, LD, PD and SS respectively.

During the BF conditions both groups showed a significant reduction of *RMS* (AIC-Full=-2546.1; AIC-Null=-2540.3; P<0.01) for DBF (*M*=0.312, *SEM*= 0.016) compared to NBF (*M*=0.327, *SEM*=0.016). EMG activity was not reduced during PBF (p=0.188).

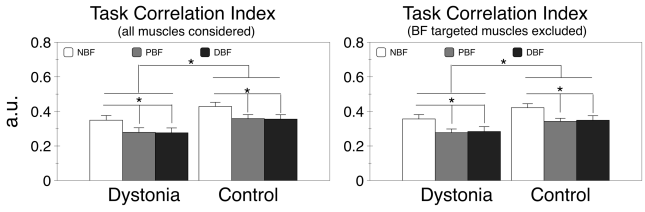

Figure 3. Left panel is showing the means and standard errors of Task Correlation Index (*TCI*) considering all upper arm muscles for both groups (Dystonia and Control) and BF conditions (NBF, PBF, DBF). Right panel is showing the means and standard errors of Task Correlation Index (*TCI*) with BF targeted muscles excluded for both groups and all the three BF conditions.

A significant effect of Group (AIC-Full=-960.87; AIC_{Null} = -955.43; P<0.01) and BF (AIC-Full=-979.03; AIC_{Null}=-955.43; P<0.001) was observed for *Err/Speed* with no interactions. *Err/Speed* ratio depicts motor skills level such that lower values represent increased ability to trade-off between accuracy and speed. The Control group showed

reduced values (*M*=0.023, *SEM*=0.004) of *Err/Speed* compared to Dystonia (*M*=0.044, *SEM*=0.005). The introduction of vibro-tactile biofeedback induced an increased *Err/Speed* ratio for both groups (PBF: *M*=0.036, *SEM*=0.004; DPF: *M*=0.037, *SEM*=0.004) compared to the condition NBF (*M*=0.030, *SEM*=0.003) (Figure 4). *VarS* showed a significant effect of both Group (AIC-Full=352.49; AIC-Null=363.88; P<0.001) and BF factors (AIC-Full=343.94; AIC-Null=363.88; P<0.01). On average *VarS* was larger for Dystonia (*M*=4.06 cm, *SEM*= 0.25 cm) compared to Control (*M*=2.54 cm, *SEM*= 0.22 cm), as well as during PBF (*M*=3.61 cm, *SEM*=0.23 cm) and DBF (*M*=3.58 cm, *SEM*=0.22 cm) conditions respect to NBF (*M*=2.75 cm, *SEM*=0.22 cm) (Figure 4). We found a significant effect on *VarT* for BF (AIC-Full=226.75; AIC-Null=295.02; P<0.001), while no significance was found for Group factor. PBF and DBF showed on average an increased temporal variability (*M*=1.088 s, *SEM*=0.194 s and *M*=0.933 s, *SEM*=0.194 s respectively) compared to NBF (*M*=0.471 s, *SEM*=0.080 s).

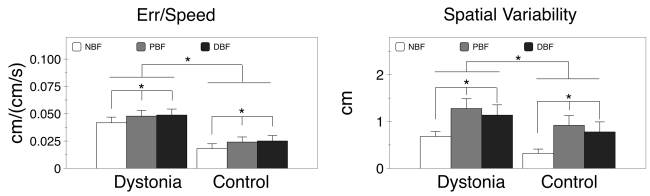

Figure 4. Left panel is showing the means and standard errors of error-speed ratio of trace (*Err/Speed*), in both groups and BF conditions. Right panel is showing the means and standard errors of Spatial Variability (*VarS*) for both groups and BF conditions.

IV. Conclusion

As shown previously, children with dystonia showed larger trial-by-trial variability and poor speed-accuracy trade-off during the figure-eight task performance [4]. The results are in line with an inability to suppress unwanted motor program components that results in higher signal-dependent noise and increased motor variability in childhood dystonia [10,12,13]. The main focus of the current study was to investigate the effects of vibro-tactile EMG-based BF on the extent of task-relevant and task-irrelevant muscle components. Results showed increased task-irrelevant unwanted muscle components when both groups went under both BF conditions. However, while muscle activity diminished with DBF, there was not significant activity decrease with PBF. The performance on the tablet decreased in terms of either trial-to-trial spatial and temporal variability, as well as the trade-off between accuracy and speed. By compelling to reduce the activity of the most crucial muscle for the task, participants were effectively exposed to a new motor task. In early stages of learning, higher performance variability has been proposed to encourage motor exploration in search of optimal task solutions [14]. Given a redundant solution task space, the learner needs to experiment to find the best possibilities for action. In this framework, the increase of task-irrelevant components during EMG-based BF may suggest an attempt to seek out new neuromotor solutions. This may explain its effect to induce higher trial-to-trial joint variability in childhood dystonia also seen in a previous study [15]. Nevertheless, Further studies are needed to test the casual relationship between changes of muscle task-related components induced by EMG-based BF and enhanced motor exploration.

The use of BF had a spread-out effect on all the upper limb muscles, even without considering the BF targeted muscle, which further confirms its ability to incite exploration of new muscle patterns. Our preliminary results further confirm the EMG-based BF to be a useful therapeutic technique to enable children with dystonia to explore different solutions and thus, pave the way for new motor skill acquisition. Augmented sensory feedback in the form of haptic-tactile vibration permits unobtrusive and portable devices that are able to direct attention to a targeted area of the body [5,8]. Therefore, vibro-tactile EMG-based BF serves as a promising therapeutic tool for improving muscle patterns in children with dystonia.

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