EMG-Based Visual-Haptic Biofeedback: A Tool to Improve Motor Control in Children With Primary Dystonia

Claudia Casellato, Alessandra Pedrocchi, Giovanna Zorzi, Lea Vernisse, Giancarlo Ferrigno, and Nardo Nardocci

***Abstract*—New insights suggest that dystonic motor impairments could also involve a deficit of sensory processing. In this framework, biofeedback, making covert physiological processes more overt, could be useful. The present work proposes an innovative integrated setup which provides the user with an electromyogram (EMG)-based visual-haptic biofeedback during upper limb movements (spiral tracking tasks), to test if augmented sensory feedbacks can induce motor control improvement in patients with primary dystonia. The *ad hoc* developed real-time control algorithm synchronizes the haptic loop with the EMG reading; the brachioradialis EMG values were used to modify visual and haptic features of the interface: the higher was the EMG level, the higher was the virtual table friction and the background color proportionally moved from green to red. From recordings on dystonic and healthy subjects, statistical results showed that biofeedback has a significant impact, correlated with the local impairment, on the dystonic muscular control. These tests pointed out the effectiveness of biofeedback paradigms in gaining a better specific-muscle voluntary motor control. The flexible tool developed here shows promising prospects of clinical applications and sensorimotor rehabilitation.**

***Index Terms*—Biofeedback, dystonia, electromyogram (EMG), haptics, sensorimotor integration.**

I. Introduction

DYSTONIA is a syndrome characterized by excessive and sustained muscle contraction causing twisting and repetitive movements, abnormal postures, or both. New insights suggest that dystonic motor impairments could also involve a deficit of sensory processing and thus of sensorimotor integration [1], [2]. Primary dystonia with childhood onset often generalizes and becomes a severe condition, causing significant motor disability and social impairment [3]. The current treatment options include pharmacological and surgical strategies [4], [5]; in children with primary dystonia, the results may be not always optimal. Deep brain stimulation (DBS) has allowed a massive improvement even if not steady in long-term and not effective for all tasks; hence specific rehabilitative trainings could represent a collateral approach for task-specific motor improvements. Which rehabilitative exercises are the most effective for dystonic people is still matter of discussion. Recently, Delnooz and colleagues [6] reviewed the effects of various paramedical treatments in primary dystonia.

The biofeedback (BF) paradigm can be defined as the use of instrumentation to make covert physiological processes more overt [7]. The use of biofeedback provides patients affected by sensorimotor impairments with opportunities to regain the ability to better assess different physiological responses and possibly to learn self-control of those responses [8]–[11]. Information about the task can facilitate the learning process, in particular enhancing the implicit motor learning [12]. This information can be classified as either "intrinsic" or "extrinsic." Intrinsic feedback refers to a person's own sensory-perceptual information that is available as a result of movement being performed. Extrinsic feedback is usually given from an outside source, like the therapist, and it has a cognitive nature [13]. The biofeedback information is therefore an additive re-afference to the central nervous system (CNS). Thus, two main features have to be defined for biofeedback: the physiological information that is desired to be fed back to the subject and the channels to provide this information.

The main clinical applications of biofeedback have been based on the idea of motor re-education through visual or audio feedback of electromyogram (EMG), positional or force parameters, in real time [14]–[17]. By applying EMG-based BF, patients suffering from sensorimotor deficits were able to volitionally control single muscle activation thanks to the increased level of awareness of their muscular activity [18]–[21]. Another sensory channel that could be exploited for BF is the tactile one, using proprioceptive and vibratory stimuli [22]. Different studies showed successful application of haptic interfaces [23]; for instance, Fielding and colleagues [24] showed that adding tactile feedback to a computer mouse enhances significantly the task performance.

As patients affected by dystonia seem to lack sufficient sensory feedback, visual and/or auditory EMG biofeedback were applied in cervical dystonia [25], [26] inducing more volitional control over the abnormally active muscles. Even using the vibration as a way of providing extra sensory input showed positive effects [27]. Specific muscle EMG biofeedback was tested also in patients with writer's cramp [28]–[30]: they learned to relax the proximal limb muscles, which showed sustained contractions during writing. Besides these studies

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C. Casellato, A. Pedrocchi, L. Vernisse, and G. Ferrigno are with the Bioengineering Department, Politecnico di Milano, 20133 Milano, Italy (e-mail: claudia.casellato@mail.polimi.it).

G. Zorzi and N. Nardocci are with the Child Neurology Department, Fondazione IRCCS Istituto Neurologico Carlo Besta, 20133 Milano, Italy.

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TABLE I
SUBJECTS' DETAILS. "HAND" INDICATES TESTED HAND (DOMINANT SIDE). BFDRS = BURKE AND FAHN DYSTONIA RATING SCALE, RANGE BETWEEN 0 AND 120

Subjects	Gender	Age	Hand	Dystonia/ age of onset	Severity (BFDRS)
1	M	12	Left	Yes / 7	25
2	M	15	Right	Yes / 6	20
3	M	18	Right	Yes / 6	26
4	M	7	Left	Yes / 9	22
5	M	10	Left	Yes / 6	46
6	F	22	Left	no	/
7	F	29	Right	no	/
8	M	23	Right	no	/
9	F	25	Right	no	/
10	F	24	Right	no	/

mainly on adults with focal and task-specific dystonia, only a few works applied BF techniques on generalized dystonia; the first attempts reported only case studies [31]. Most recently, Young *et al.* showed promising results suggesting that visual biofeedback reduces co-contraction and overflow during motor tasks (not directly related to daily activities) in children with dystonic symptoms of different aetiologies [32], [33].

The promising results about a possible relevant role of haptics in the training of perceptual motor skills in virtual environments represent a strong motivation to exploit this approach in movement disorders.

Thus, in the present work we developed an innovative integrated setup providing EMG-based visual-haptic biofeedback during upper limb movements and we investigated a group of children with primary dystonia in order to determine the effect of two-channel biofeedback on dystonic symptoms as measured through EMG activity. Using both visual and haptic channels arises from current theories on sensory integration which suggest that receiving information from multiple sensory modalities can produce better performance than from a single modality.

II. METHODS

A. Subjects

Five children affected by primary dystonia (DYT1, DYT6, and genetically undefined), with different severities rated by the Burke and Fahn Dystonia Rating Scale (BFDRS), were recruited for this study. Five healthy subjects were recruited as a control group. Details are reported in Table I.

Participants or their parents or guardian gave written informed consent for the study in accordance with the Institutional Review Board of the Neurological Institute Carlo Besta.

B. Experimental Setup and Protocol

The setup we used was composed of a haptic device (Phantom Omni by Sensable, 1 kHz for real-time loop, maximum nominal force 3.3N) and an EMG device (Porti System, TMSi, 2048 Hz). The haptic–graphic interface was built up for the required task.

The real-time control algorithm was developed in Visual C++, so as to synchronize the Phantom position-force loop with the EMG signal reading; the EMG values were used to proportionally modify visual and haptic features of the interface. The raw EMG data given by the TMSi were preprocessed (high-pass filtering at 5 Hz, rectification and 40-sample moving average) and, in order to make feasible the EMG reading and the corresponding parameters updating into the Phantom control loop, were under-sampled at 20 Hz. The haptic device gives back a force feedback based on the end-effector position, thus it depends on the interactions with the elements built in the virtual environment.

The first step consisted of a subject-specific calibration phase on the dominant arm; the maximum voluntary contraction (MVC) and the $\mathrm{EMG}_{\mathrm{rest}}$ from the brachioradialis muscle were recorded and supplied to the control algorithm. The subject was asked to perform three trials keeping the maximum isometric effort for 5 s, while the real-time EMG signal was displayed in front of him.

Then, the task interface was shown, the subject was asked to follow a drawn spiral path lying on a virtual table, by moving the Phantom end-effector. Two 3-D touchable spheres (their color changed at touch) were added in the environment, to identify the start and the final points. Moreover, to check and facilitate the subject to stay leaning on the table while drawing, a bar was added on the screen: it became black when the subject leaned on the virtual table, white otherwise; this touch-based signal was stored by the control algorithm. The integration developed here with the EMG signals provides further real-time changes of the interface: the higher the EMG level, the higher is the virtual table friction and the background color proportionally moves from green to red. In particular, the acquired EMG values were normalized (nEMG) on the subject's MVC and were translated with an offset equal to the subject's rest baseline $(\mathrm{EMG}_{\mathrm{rest}})$

$$\mathrm{nEMG} = \frac{(\mathrm{EMG\text{-}EMG}_{\mathrm{rest}})}{\mathrm{MVC}}.$$

The friction parameter of the path surface (ν) was linearly dependent from nEMG

$$\nu = 2 \cdot \mathrm{nEMG}.$$

Thus, $\nu = 0$ when $\mathrm{nEMG} = 0\%$ and $\nu = 1$ when $\mathrm{nEMG} = 50\%$ MVC. The friction force rendered by the device depends on ν and on the exerted load perpendicular to the virtual table. Just as indication, considering a constant and slight pushing during the tracking task, as required, the friction force intensity could range from 0 to 2.5 N, depending on ν.

Analogously, the background color (*Red Green Blue*) was linearly dependent from nEMG

$$[R \quad G \quad B] = [2 \cdot \mathrm{nEMG} \quad 1 - 2 \cdot \mathrm{nEMG} \quad 0].$$

Thus, RBG $= [0 \quad 1 \quad 0]$, i.e., green, when $\mathrm{nEMG} = 0\%$ and RBG $= [1 \quad 0 \quad 0]$, i.e., red, when $\mathrm{nEMG} = 50\%$ MVC. Above 50% MVC, the parameters kept the maximum level as

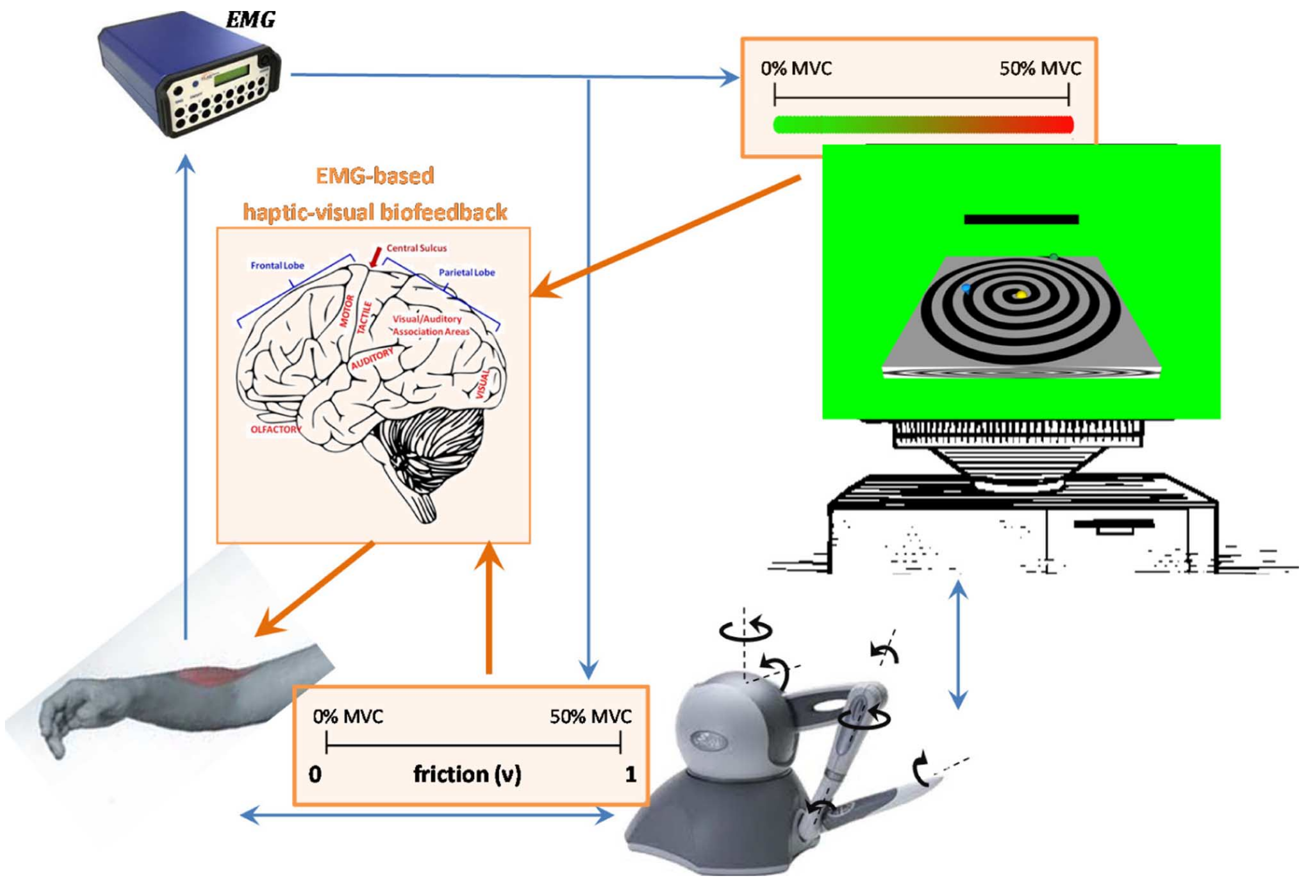

Fig. 1. Integrated setup: EMG device for brachioradialis activity recording, haptic device, and task interface. Visual (color scale) and haptic (friction tuning) signals, updated in real-time based on EMG, are supplied to subject as biofeedback, as augmented re-afference to CNS.

50% MVC. The setup is depicted in Fig. 1. The 3-D displacement of end-effector and the EMG signals of each trial were recorded and elaborated offline.

The subject performed a few trials of the task for familiarization and received an explanation of the biofeedback codes meaning, i.e., with BF, he was asked to achieve the task naturally keeping the color far from red as much as possible and the surface friction as low as possible. Thus, the first series of five trials without any biofeedback, i.e., uniform color and null friction, was carried out (noBF). Immediately, the second series of five trials with biofeedback was performed (BF).

C. Data Analysis

The data analyses were carried out with Matlab (Mathworks) and with StatSoft.

Each trial was identified by the 3-D spheres touching events; this cut was performed on the kinematic data and on the synchronized EMG data (Fig. 2).

The root mean square (RMS) was used as an estimation of the activity level [34]

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{k=1}^{N} \mathrm{nEMG}_k^2} \cdot 100\ [\%]$$

where N is the number of samples.

Possible phases of not leaning on the table, e.g., when the subject fell down from table and tried to go back on it, were identified by the touch control bar and counted out of parameter estimations.

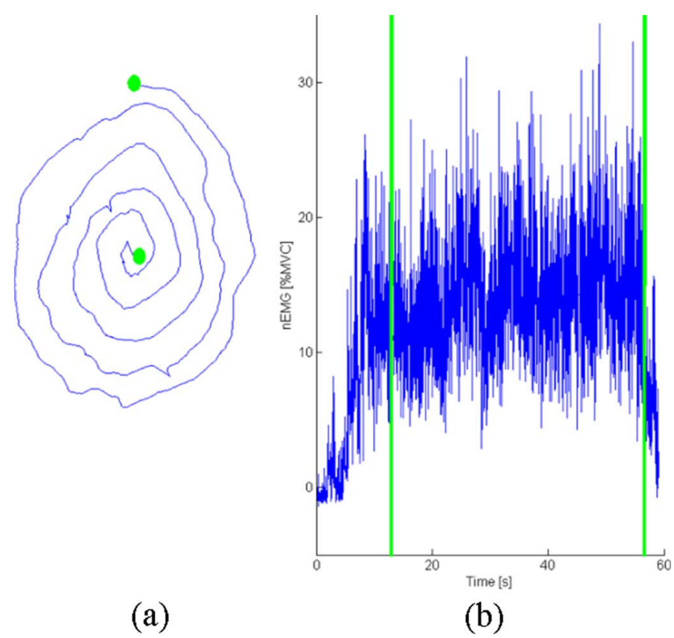

Fig. 2. One exemplificative trial of kinematics and EMGs. (a) Recorded end-effector kinematics. (b) Recorded EMG, with the onset and end instants depicted through the vertical green lines (spheres touch events); EMG values are indicated as % MVC.

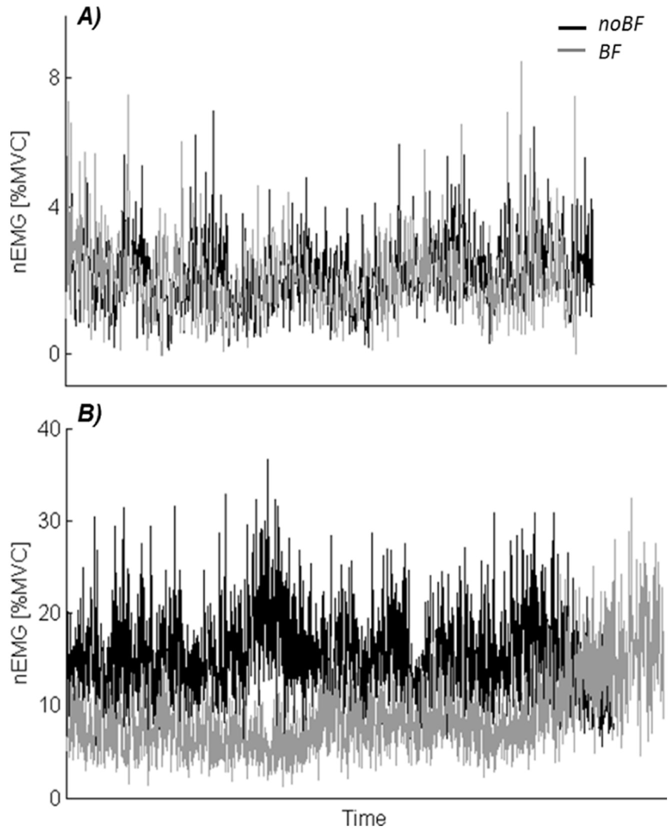

Fig. 3. Exemplificative EMG signals, for one healthy (A) and one dystonic (B). For each, one trial without BF (black) and one with BF (grey) are reported, from the onset to the end instants.

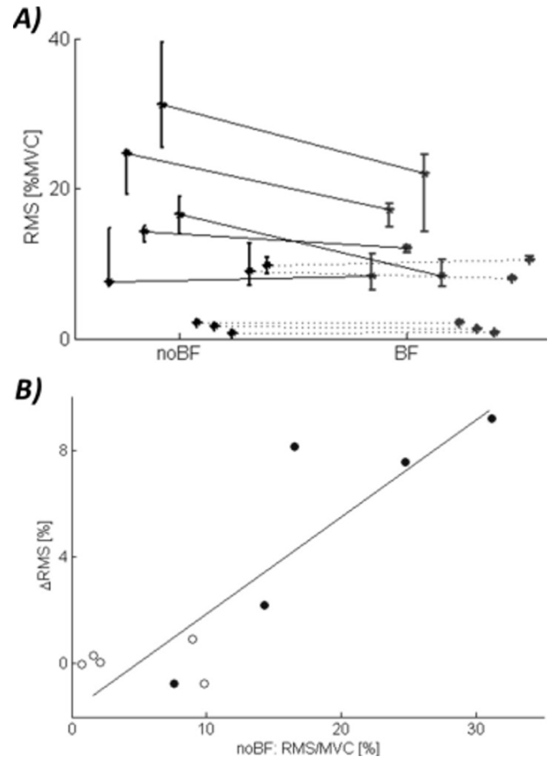

Fig. 4. (A) For each subject, EMG RMS median values and 75th–25th percentiles are reported (noBF and BF). Straight lines: dystonic; dashed lines: healthy. (B) Regression between RMS in reference condition (noBF) and ΔRMS (noBF-BF). Filled circles: dystonic; empty circles: healthy.

As a rough evaluation of the kinematic outcome, a similarity index between a representative healthy smooth spiral and each of the ten spiral drawings (5 noBF and 5 BF), for each patient was computed, as Frechet distance (0 when the two curves are identical).

D. Statistical Analysis

The RMS values for each subject, for both noBF and BF, were estimated as the median values among the corresponding five trials. The variability was computed as interquartile range (IQR), i.e., 75th–25th percentiles distance. A two-way repeated measures ANOVA test was applied on all subjects. The within-subject factor was the experimental condition, i.e., noBF/BF, and the between-subject factor was the group, i.e., dystonic/healthy.

After the ANOVA test, a *post hoc* test Scheffé was performed to investigate the responsible factors for the potential significant effects.

In order to check whether an overall trend of improvement along the ten repetitions could bias the comparison between conditions (noBF versus BF), a test for trend significance detection was applied (Jonckheere–Terpstra test, suitable for dataset with few repetitions; null hypothesis: absence of a monotonic trend).

III. Results

Fig. 3 shows recorded EMGs from one healthy and one dystonic subject during a trial without BF and a trial with BF. Using a within-subject approach, it is qualitatively evident that, while for the healthy subject the BF did not have any impact on the muscle activation, for the dystonic child the contraction level decreased when BF was activated.

The two-way ANOVA test on the median RMS values, for each subject without and with BF, outlined multiple factor roles. Both the between-group factor and the within-subject experimental condition produced significant effects (dystonic/healthy: $F = 9.03$, $p = 0.017$; noBF/BF: $F = 7.58$, $p = 0.025$); also the factor interaction determined a significant result ($F = 6.7,\ p = 0.029$).

The *post hoc* Scheffè test highlighted the pairwise differences; the noBF/BF factor defined two statistically distinguishable populations within the Dystonic group ($p = 0.03$), while it was clearly negligible into the healthy group ($p = 0.99$). These results are shown in Fig. 4.

The trend significance test on RMS values along the trial sequence for all subjects verified the absence of a monotonic trend ($\mathrm{JT} = 1.2,\ p = 0.11$).

Thus, the BF had a dystonia-related significant impact on the measured outcome.

To exclude a role of the trial duration on this outlined difference between noBF and BF conditions within the dystonic group, a pair-matched nonparametric test (Wilcoxon) was performed on the median duration values: the within-subject movement duration was comparable regardless of the BF ($Z = 1.75, p = 0.08$).

Furthermore, the $\Delta\mathrm{RMS}$, i.e., the difference between $\mathrm{RMS}_{\mathrm{noBF}}$ and $\mathrm{RMS}_{\mathrm{BF}}$, was computed for each subject.

TABLE II
MEDIAN AND IQR OF SIMILARITY INDEXES FOR EACH DYSTONIC SUBJECT IN TWO CONDITIONS (NOBF/BF)

Dystonic subjects	noBF		BF	
	median	**IQR**	**median**	**IQR**
1	44,6	12,3	37,8	20,9
2	17,4	2,1	17,4	4,1
3	51,5	38,6	39,3	7,0
4	23,5	34,3	23,0	51,1
5	21,7	27,4	13,1	6,4

This value was correlated (linear regression) with the local impairment measured as the EMG activity (RMS) in the standard condition (noBF). Such a correlation was significant ($R = 0.88, p = 0.0007$): the higher the muscle-specific impairment, the higher the BF effect was on muscular control. These findings are displayed in Fig. 4(b).

The same two-way ANOVA test applied on the variability index (IQR) outlined a significant effect both due to the group ($F = 6.53$, $p = 0.03$) and due to the condition ($F = 11.3$, $p = 0.01$), but not to the factor interaction. This means that the movement variability, as expected, was higher for dystonic than for healthy; but the BF did not significantly affect the inter-trial variability in a selective way, i.e., not producing a distinguishable effect between dystonic and healthy subjects.

Concerning the kinematic evaluation, Table II reports the median and IQR of similarity indexes for each dystonic subject in the two conditions (noBF/BF). No significant effect due to the condition was found out (repeated measures ANOVA), even if a tendency to decrease such index (i.e., improvement in the kinematic performance) when BF acts could be noticed.

IV. DISCUSSION

The present work proposed an innovative integrated setup for EMG-based visual-haptic biofeedback during upper limb movements. Pilot tests demonstrated that children with primary dystonia were able to reduce the level of muscle contraction while provided with this biofeedback during a spiral drawing, thus outlining the effectiveness of BF paradigms in gaining a better voluntary motor control.

The design of our setup addresses the main features of an effective sensorimotor training based on BF paradigms. First of all, the training must be functional and dynamic, asking the subject to perform tasks related to the activities of daily living (ADL). Second, depending on the movement protocols and on the target pathology, the most relevant information to be fed back has to be appropriately selected. Third, the presentation modality of this information has to be: 1) intuitive and easy-to-understand, to avoid information overloading problems; 2) relevant for knowledge of performance; 3) attractive and motivating to keep the subject attentive. Presented information such as lines on a computer screen or simple beeps can be neither intuitive nor attention grabbing, thus making participants, especially children, distracted quickly [35]. Thus, we have tried to overcome these issues. We exploited computerized graphics and haptic robotics, since they allow visual and kinesthetic interactions with the virtual environment. Through a simple interview at the session end, we collected each subject's opinion concerning the protocol acceptability (pleasant, fair, difficult, impossible). Two of them defined the task requirements (with and without BF) as fair; two pleasant and one, the youngest one, difficult due to the spiral shape to be followed. The spiral drawing can be considered a quite complex functional task related to writing, a relevant gesture of daily activities often impaired in dystonic children, and it is used in clinical practice for disease assessment. The EMG signal was related to one of the most involved muscles in such task, the brachioradialis; using only one signal avoids any information overloading or complex information fusion algorithm difficult to be decoded by children.

The clinical tests foresaw only few trials for each experimental condition, to keep away fatigue and demotivation which could have introduced bias effects on the results.

These findings, interestingly, showed a significant decrease of muscle activity when the dystonic population was provided with BF. No differences at all were found out for healthy population. This promising BF effect was moreover related to the muscle-specific impairment related to the task: the more severe the movement disorder was, the more the augmented feedback represented a useful information to enhance specific motor performance.

The combination of proprioception with additive source of sensory information allows CNS to better drive and modulate the actuators' activity [36].

It is worth noting that in the present study the output measurement does not come only from clinical observation-based scales but from electrophysiological quantitative parameters; that has the advantage of requiring a lower patient number to demonstrate the treatment success [6].

The neurological mechanisms underlying the effectiveness of biofeedback training are unclear; however, Basmajian [37] has suggested two possibilities: either new pathways are developed, or an auxiliary feedback loop recruits existing cerebral and spinal pathways, activating unused or underused synapses in executing motor commands [19], [38]–[41].

This study has developed and tested an innovative BF tool, outlining its interesting application for sensorimotor rehabilitation and functional training to improve motor control, in combination with other conventional techniques. The setup flexibility allows to define user-specific protocols and interfaces and the control algorithm is suitable for customization of the relationships between the physiological variable driving the BF and the rendered multimodal information. For instance, considering more complex tasks asking for interactions with virtual objects, other haptic proprieties could be tuned based on EMG signals, such as texture, damping features, and so on. Moreover, the BF effectiveness of each sensory modality could be evaluated stand alone, so as to define the most effective multimodal combination, eventually subject-specifically weighted.

Furthermore, the present data suggest that the provided information needs to be minimized in order to increase the technique acceptability, especially for very young children. For instance, the leaning-check bar could be displayed during the familiarization phase but not during the training, since it could overload the user with information not useful for motor control enhancing.

The whole integrated setup permits a detailed quantitative characterization of functional motor tasks, precious for movement disorders assessment, and its simple working mechanisms fit well in clinical application needs. Since the augmented feedback can improve motor learning, it can be expected that a BF continued training could establish new sensory engrams, applicable in performing movements without additive feedback and able to generalize on real-world tasks. Because of several promising results of BF on movement disorders, very recent research is proposing in-home BF systems, thus allowing a more natural and continuous training [42].

Some limitations of the present study are worth comments and indicate the directions for future perspectives. First, the population sample is very limited and future studies will have to increase it and take into account an aged-matched control group, thus allowing a between-group analysis and an accurate correlation with clinical scale scores. Therefore, a systematic clinical assessment will be designed as a crossover study with a randomized order between control condition (noBF) and treatment (BF). Moreover, in order to systematically validate the BF effectiveness, the clinical study will have to measure the outcome indexes before, post and in a follow-up assessment. Some studies, on cervical dystonia, indeed, showed that sometimes the improvement observed during the session did not persist in a follow-up period [25].

Second, the current setup does not permit severe patients to perform the task due to the inability to autonomously initiate any functional movement. The introduction of robot mechanical active assistance for motor task initialization and/or for antigravity support will overcome this limitation enlarging the potential user group.

In conclusion, a clinical study will aim to validate the preliminary promising findings of the new BF paradigm in dystonia proposed here.

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References

[1] A. Quartarone, V. Rizzo, and F. Morgante, "Clinical features of dystonia: A pathophysiological revisitation," *Curr. Opin. Neurol.*, vol. 21, pp. 484–490, 2008.

[2] T. D. Sanger and S. N. Kukke, "Abnormalities of tactile sensory function in children with dystonic and diplegic cerebral palsy," *J. Child Neurol.*, vol. 22, pp. 289–293, 2007.

[3] C. Casellato, G. Zorzi, A. Pedrocchi, G. Ferrigno, and N. Nardocci, "Reaching and writing movements: Sensitive and reliable tools to measure genetic dystonia in children," *J. Child Neurol.*, vol. 26, pp. 822–829, 2011.

[4] M. Kojovic, A. Caronni, M. Bologna, J. C. Rothwell, K. P. Bhatia, and M. J. Edwards, "Botulinum toxin injections reduce associative plasticity in patients with primary dystonia," *Mov. Disord.*, vol. 26, pp. 1282–1289, 2011.

[5] A. Haridas *et al.*, "Pallidal deep brain stimulation for primary dystonia in children," *Neurosurgery*, vol. 68, pp. 738–743, 2011.

[6] C. C. Delnooz, M. W. Horstink, M. A. Tijssen, and B. P. van de Warrenburg, "Paramedical treatment in primary dystonia: A systematic review," *Mov. Disord.*, vol. 24, pp. 2187–2198, 2009.

[7] J. V. Basmajian, *Biofeedback: Principles and Practice for Clinicians*, 3rd ed. Baltimore, MD, USA: Williams Wilkins, 1989.

[8] E. Dursun, N. Dursun, and D. Alican, "Effects of biofeedback treatment on gait in children with cerebral palsy," *Disabil. Rehabil.*, vol. 26, pp. 116–120, 2004.

[9] J. Moreland and M. A. Thomson, "Efficacy of electromyographic biofeedback compared with conventional physical therapy for upper-extremity function in patients following stroke: A research overview and meta-analysis," *Phys. Ther.*, vol. 74, pp. 534–547, 1994.

[10] E. R. Hilgard and G. H. Bower, "Recent developments," in *Theories of Learning*, 4th ed. Englewood Cliffs, NJ, USA: Prentice-Hall, 1975, pp. 550–605.

[11] H. Huang, S. L. Wolf, and J. He, "Recent developments in biofeedback for neuromotor rehabilitation," *J. Neuroeng. Rehabil.*, vol. 3, pp. 11–11, 2006.

[12] L. A. Boyd and C. J. Winstein, "Impact of explicit information on implicit motor-sequence learning following middle cerebral artery stroke," *Phys. Ther.*, vol. 83, pp. 976–989, 2003.

[13] P. M. van Vliet and G. Wulf, "Extrinsic feedback for motor learning after stroke: What is the evidence?," *Disabil. Rehabil.*, vol. 28, pp. 831–840, 2006.

[14] L. Comolli, S. Ferrante, A. Pedrocchi, M. Bocciolone, G. Ferrigno, and F. Molteni, "Metrological characterization of a cycle-ergometer to optimize the cycling induced by functional electrical stimulation on patients with stroke," *Med. Eng. Phys.*, vol. 32, pp. 339–348, 2010.

[15] S. Ferrante, E. Ambrosini, P. Ravelli, E. Guanziroli, F. Molteni, G. Ferrigno, and A. Pedrocchi, "A biofeedback cycling training to improve locomotion: A case series study based on gait pattern classification of 153 chronic stroke patients," *J. Neuroeng. Rehabil.*, 2011.

[16] E. Ambrosini, S. Ferrante, G. Ferrigno, F. Molteni, and A. Pedrocchi, "Cycling induced by electrical stimulation improves muscle activation and symmetry during pedaling in hemiparetic patients," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 20, no. 3, pp. 320–330, 2012.

[17] E. Ambrosini, S. Ferrante, A. Pedrocchi, G. Ferrigno, and F. Molteni, "Cycling induced by functional electrical stimulation in post-acute hemiparetic patients: A Randomized controlled trial," *Stroke*, vol. 42, pp. 1068–1073, 2011.

[18] C. K. Fernando and J. V. Basmajian, "Biofeedback in physical medicine and rehabilitation," *Biofeedback Self Regul.*, vol. 3, pp. 435–455, 1978.

[19] S. L. Wolf, "Electromyographic biofeedback applications to stroke patients," *Phys. Ther.*, vol. 63, pp. 1448–1459, 1983.

[20] J. V. Basmajian, "Control and training of individual motor units," *Science*, vol. 141, pp. 440–441, 1963.

[21] J. V. Basmajian, "Research foundations of EMG biofeedback in rehabilitation," *Biofeedback Self Regul.*, vol. 3, pp. 275–298, 1988.

[22] M. A. Lebedev and M. A. Nicolelis, "Brain-machine interfaces: Past, present and future," *Trends Neurosci.*, vol. 29, pp. 536–546, 2006.

[23] C. Casellato, A. Pedrocchi, G. Zorzi, G. Rizzi, G. Ferrigno, and N. Nardocci, "Error-enhancing robot therapy to induce motor control improvement in childhood onset primary dystonia," *J. Neuroeng. Rehabil.*, vol. 9, no. 46, 2012.

[24] M. Fielding and S. Nahavandi, "Haptics mouse for visually impaired," *Mechatron. Robot.*, pp. 356–361, 2004.

[25] B. Leplow, "Heterogeneity of biofeedback training effects in spasmodic torticollis: A single-case approach," *Behav. Res. Ther.*, vol. 28, pp. 359–365, 1990.

[26] J. Korein and J. Brudny, "Integrated EMG feedback in the management of spasmodic torticollis and focal dystonia: A prospective study of 80 patients," *Res. Publ. Assoc. Res. Nerv. Ment. Dis.*, vol. 55, pp. 385–426, 1976.

[27] A. A. Leis, M. R. Dimitrijevic, J. S. Delapasse, and P. C. Sharkey, "Modification of cervical dystonia by selective sensory stimulation," *J. Neurol. Sci.*, vol. 110, pp. 79–89, 1992.

[28] K. K. Deepak and M. Behari, "Specific muscle EMG biofeedback for hand dystonia," *Appl. Psychophysiol. Biofeedback*, vol. 24, pp. 267–280, 1999.

[29] M. A. O'Neill, K. A. Gwinn, and C. H. Adler, "Biofeedback for writer's cramp," *Amer. J. Occup. Ther.*, vol. 51, pp. 605–607, 1997.

[30] H. J. Berger, S. P. van der Werf, C. A. Horstink, A. R. Cools, W. J. Oyen, and M. W. Horstink, "Writer's cramp: Restoration of striatal D2-binding after successful biofeedback-based sensorimotor training," *Park. Relat. Disord.*, vol. 13, pp. 170–173, 2007.

[31] E. Shahar, M. Nowaczyk, and R. C. Tervo, "Rehabilitation of communication impairment in dystonia musculorum deformans," *Pediatr. Neurol.*, vol. 3, pp. 97–100, 1987.

[32] S. J. Young, J. van Doornik, and T. D. Sanger, "Visual feedback reduces co-contraction in children with dystonia," *J. Child Neurol.*, vol. 26, pp. 37–43, 2011.

[33] S. J. Young, J. van Doornik, and T. D. Sanger, "Finger muscle control in children with dystonia," *Mov. Disord.*, vol. 26, pp. 1290–1296, 2011.

[34] F. D. Farfán, J. C. Politti, and C. J. Felice, "Evaluation of EMG processing techniques using information theory," *Biomed. Eng. Online*, vol. 12, pp. 9–72, 2010.

[35] J. Nash, P. D. Neilson, and N. J. O'Dwyer, "Reducing spasticity to control muscle contracture of children with cerebral palsy," *Dev. Med. Child Neurol.*, vol. 31, pp. 471–480, 1989.

[36] C. Casellato, M. Tagliabue, A. Pedrocchi, C. Papaxanthis, G. Ferrigno, and T. Pozzo, "Reaching while standing in weightlessness: A new postural solution to simplify movement control," *Exp. Brain Res.*, vol. 216, pp. 203–215, 2012.

[37] J. V. Basmajian, "Clinical use of biofeedback in rehabilitation," *Psychosomatics*, vol. 23, pp. 67–73, 1982.

[38] C. Casellato, S. Ferrante, M. Gandolla, N. Volonterio, G. Ferrigno, G. Baselli, T. Frattini, A. Martegani, F. Molteni, and A. Pedrocchi, "Simultaneous measurements of kinematics and fMRI: Compatibility assessment and case report on recovery evaluation of one stroke patient," *J. Neuroeng. Rehabil.*, vol. 7, no. 49, 2010.

[39] M. Gandolla, S. Ferrante, C. Casellato, G. Ferrigno, F. Molteni, A. Martegani, T. Frattini, and A. Pedrocchi, "fMRI brain mapping during motion capture and FES induced motor tasks: Signal to noise ratio assessment," *Med. Eng. Phys.*, vol. 33, pp. 1027–1032, 2011.

[40] E. Biffi, A. Menegon, F. Piraino, A. Pedrocchi, G. B. Fiore, and M. Rasponi, "Validation of long-term primary neuronal cultures and network activity through the integration of reversibly bonded microbioreactors and MEA substrates," *Biotechnol. Bioeng.*, vol. 109, pp. 166–175, 2012.

[41] D. Ghezzi, A. Menegon, A. Pedrocchi, F. Valtorta, and G. Ferrigno, "A micro-electrode Array device coupled to a laser-based system for the local stimulation of neurons by optical release of glutamate," *J. Neurosci. Methods*, vol. 175, pp. 8–70, 2008.

[42] R. Bloom, A. Przekop, and T. D. Sanger, "Prolonged electromyogram biofeedback improves upper extremity function in children with cerebral palsy," *J. Child Neurol.*, vol. 25, pp. 1480–1484, 2010.

Claudia Casellato received the Ph.D. degree in bioengineering from the Politecnico di Milano, Milan, Italy, in 2011.

Her research activities are related to neuro-robotic and neuro-motor control mechanisms. She is involved in several projects such as EU project MUNDUS (upper limb neuroprostheses); EU project REALNET (cerebellum-inspired learning), ELITE-S2 on International Space Station (motor control in weightlessness), and rehabilitation tool development for movement disorders (EMG, haptics, kinematics integration).

Alessandra Pedrocchi received the Ph.D. degree in bioengineering from the Politecnico di Milano, Milan, Italy, in 2001.

Since June 2008, she has been an Assistant Professor in the Department of Bioengineering, Politecnico di Milano, where she teaches neuroengineering in the Master of Science in Bioengineering program. Her research activities are carried on at the NearLab in the field of biomechanics in motor control, neuroengineering and neurorehabilitation. She is Project Manager of MUNDUS project (FP7 ICT-2009.7.2) and the Politecnico PI for REALNET project (FP7 Obj ICT-2009.6).

Giovanna Zorzi is a Pediatric Neurologist, at the Child Neurology Department at Fondazione IRCCS Istituto Neurologico "C Besta", Milan, Italy. She is involved in clinical and therapeutic research in the field of pediatric movement disorders.

Lea Vernisse is an Engineer in bioinformatics and modelling at INSA de Lyon, Villeurbanne cedex, France.

Giancarlo Ferrigno is full Professor of bioengineering and medical robots at the Politecnico di Milano, Milan, Italy. He is founder of the Neuroengineering and Medical robotics laboratory at the Politecnico di Milano. His research interests encompass neuroengineering for rehabilitation and neurophysiological research and surgical robotics.

Nardo Nardocci is a Pediatric Neurologist and the Chair of Child Neurology Department at Fondazione IRCCS Istituto Neurologico "C Besta", Milan, Italy. He received medical training at the University of Pavia before moving to the Istituto Neurologico "C Besta" of Milan. The Fondazione IRCCS Istituto Neurologico "C Besta" is a leading center in neuroscience for diagnoses and treatments of neurological diseases in adults and children and basic and clinical research in neurology. His research interests are focused on the study of clinical and therapeutic aspects of pediatric movement disorders, in particular dystonia.