 doi:10.20944/preprints202001.0021.v1

Robot-Assisted Therapy Influence on Kinematic and EMG Activity in the Upper Limb for Children with Cerebral Palsy

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 doi:10.20944/preprints202001.0021.v1

Abstract

AIM To develop an index for quantitative assessment of the upper limb motor function in children with cerebral palsy before and after robot-assisted therapy.

METHOD An upper limb motor function index was developed using kinematic, surface electromyography and three-axis inertial measurements unit data collected from 15 children with cerebral palsy (CP) and 15 typically developed children. Children with CP underwent 18 robot-assisted therapy sessions with the REAplan device. All children were evaluated, using kinematic data from the REAplan, electromyography and three-axis inertial measurements unit readings from its accelerometer. A principal component analysis was conducted to produce an evaluation index, which is able to detect the deviation from the upper limb motor function of typically developing children group. Children with CP were evaluated twice before and after the intervention with Box and Blocks test and Finger-To-Nose test. The discriminative and concurrent validity of the upper limb motor function index were investigated.

RESULTS The upper limb motor function index was higher in children with CP post therapy ($p<0.001$). Finger-To-Nose test values improved after robot-assisted therapy ($p<0.03$). A weak but positive correlation was observed between upper limb motor function index and clinical tests ($\rho=0.012$, $p=0.95$ and $\rho=0.13$, $p= 0.54$ for Box and Blocks test and Finger-To-Nose test respectively).

INTERPRETATION The upper limb motor function index successfully differentiated between the typically developing children and children with CP and was effective in assessing the improvement of the upper limb motor function after robot-assisted therapy. The upper limb motor function index could be extended to assess and monitor rehabilitation therapies of other populations, such as those with stroke and Parkinson's disease.

 doi:10.20944/preprints202001.0021.v1

What this paper adds:

- The upper limb motor function index offers an objective alternative to the clinical scales.
- The upper limb motor function index can show whether there was any significant change in kinematic and electromyography activity in the upper limb after intervention.
- The REAplan improved proximal movement patterns in children with cerebral palsy.

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Abbreviations

AAC	Average Amplitude Change
ACC	Accelerometer
AHA	The Assisting Hand Assessment
AR	Auto Regression coefficient
BBT	Box and Block Test
CC	Cepstrum Coefficients
CP	Cerebral Palsy
FMA	Fugl-Meyer Assessment
EMG	Electromyography
FTN	Finger-To-Nose test
GDI	Gait Deviation Index
IEMG	Integrated EMG
IMU	Inertial Measurement Unit
IMU-ACC	IMU readings from accelerometer
MAS	The Modified Ashworth Scale
MAUULF	The Melbourne Assessment of Unilateral Upper Limb Function
MFL	Maximum fractal length
MSS	Mean Spike Slope
MU	Motor Unit
PCA	Principal Component Analysis
QUEST	The Quality of Upper Extremity Skills Test
Robot-AT	Robot-Assisted Therapy
SM2	2nd spectral moment
UL	Upper Limb

 doi:10.20944/preprints202001.0021.v1

ULMFI	Upper limb motor function index
WL	Waveform Length
ZC	Zero Crossing

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Introduction

Cerebral palsy (CP) is a group of neurodevelopmental disorders caused by a static insult to the developing brain and affecting movement and posture [1, 2]. It is also the most prevalent type of physical disability in children [3]. Upper limb (UL) dysfunction in particular, is one of the most important disabling symptoms and has a major negative effect on children's quality of life [4].

Although CP is a lifelong disability, there are a variety of therapeutic interventions used to improve functional abilities, treat spasticity-related pain and impact children's quality of life. Recently, robotic rehabilitation devices were developed and employed for the pediatric population with neuromotor disorders [5]. Research studies have shown that the use of robotic rehabilitation devices can offer a great improvement in UL motor function compared to conventional therapies [6, 7].

To determine the amount of clinically important change after these interventions and decide the patient's robotic rehabilitation needs in the future, the evaluation of UL motor function plays an important role. In most of these studies, the assessment of UL motor function improvement was guided by clinical scales. A variety of assessment tools were used [8], the Fugl-Meyer Assessment (FMA) [9]; the Modified Ashworth Scale (MAS) [10], the Quality of Upper Extremity Skills Test (QUEST) [11], the Melbourne Assessment of Unilateral Upper Limb Function (MAUULF)[12], the Assisting Hand Assessment (AHA)[13] and the Box and Block Test (BBT) [14]. Despite having proved their validity in assessing UL motor function, these scoring systems are still considered a descriptive and subjective evaluation. Moreover, these scoring systems rely on the clinicians' expertise, leading to non-consideration of pathological mechanisms, limited accuracy and an underestimation of child's actual performance [15-17].

On the other hand, few studies have suggested testing UL motor function using kinematic, kinetic and dynamic data, before, during and after the Robot-AT. According to the meta-analysis of V. Falzarano et al. [5], most of these studies presented a clinical application with kinematic outcome measures. In five clinical protocols, the kinematic values - smoothness and motor performance - improved significantly in the training group compared to the control group. Gilliaux et al. [18] used the REAplan [19] to compare

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robotic rehabilitation with traditional therapy in children with CP. Greater smoothness ($p < 0.01$) and manual dexterity ($p < 0.04$) were observed in the training group when compared to the control group. Two other studies using the same device; Armeo Spring system, concluded that significant improvements were present in terms of UL kinematics such as movement duration, velocity of movement execution, smoothness and Number of Unit Number [20, 21].

Quantitative electromyography (EMG) analysis has been widely used in pattern recognition, rehabilitation training and motor control analysis. To the knowledge of the authors, only a few recent studies used EMG features to assess the effectiveness of robot-AT. For example, Zadnia et al. [22] showed that Shannon entropy could provide an accurate visual biofeedback for reduction of spasticity in patients with a stroke. Another research study found that implementing an EMG-based model of muscle health in a rehabilitative elbow brace has the potential of assessing patients' recovery from Musculoskeletal (MSK) elbow trauma [23]. Some authors advised to incorporate EMG-measurements for the assessment of UL movement characteristics in children with CP [24]. However, no study has examined effectiveness of assistive technology interventions for CP children with kinematic and EMG measurements.

In this research paper, an index for quantitative assessment of the upper limb motor function in children with CP after robot-AT is proposed, based on fused data from kinematic, EMG and inertial measurements unit readings from accelerometer (IMU-ACC) measurements. A group of typically developing (TD) children was included representing the normal pattern of the task performance. The upper limb motor function index (ULMFI) was developed using a Euclidean distance similar to the GDI [25].

We hypothesized that robot-AT would increase ULMFI values in children with CP and that levels of muscle activation would be closer to those of TD children.

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Methods

The methods' section is divided as follows:

First, we will present participants and experimental protocol. Second, we will describe the strategy of feature extraction and selection, and finally we will illustrate all steps of data analysis including the concurrent and discriminative validity.

Participants and experimental protocol

15 CP children (mean age: 9 y 5 mo, interquartile range [IQR] 8:10y) and 15 TD children (mean age: 8 y 2 mo, [IQR] 6–11y) were recruited in the data collection experiment. The inclusion criteria consist of: a history of CP, a maximum age of 14 years and the ability to understand or perform the given tasks. Furthermore, TD children needed to not having had a history of joint or neurological disorders. Among the exclusion criteria were botulinum toxin injections within six months before measurements or previous orthopedic surgery in the UL for CP children. CP patients were recruited from a school for children with physical disabilities (École Victor-Doré, Montréal, Qc, Canada). The study was approved by the Research Ethics Boards of Ste. Justine Hospital (protocol code: 2017-1458). The informed consent was obtained from all subjects prior to their participation. The patients' characteristics are described in Table 1.

Table 1 Demographic characteristics.

	Cerebral palsy	Typically developing
n	15	15
Age, y: mo (IQR)	9:5 (8:0-10:0)	8:2 (6:0-11:0)
Gender, males/females	8/7	10/5
Box and Block test, mean	21.85 (10.40)	-
Coordination proximal, mean	15.23 (6.43)	-
MACS levels	I: 3	-
	II: 6	-
	III: 5	-
	IV: 1	-

IQR, interquartile range; MACS, Manual Ability Classification System

In this study, every CP child underwent a 10-week training with the end-effector REAplan robot [26] with two weekly sessions. Each session lasted for 45 min. During each session

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using REAplan, children performed four standard tasks; two unidirectional tasks (a target task and a free Amplitude task) and two geometrical tasks (circle task and a square task), with the supervision of their occupational therapist. They were evaluated using REAplan over two sessions: before the intervention and at the end of the 10-week program. Before and after the intervention, occupational therapists adopted two clinical scales to assess the motor function of the UL of the CP children, namely the Box and Block test (BBT; to measure unilateral gross manual dexterity) and the Finger-To-Nose test (FTN; to quantify the degree of impaired coordination).TD children were evaluated once using the REAplan.

Datasets from two CP subjects were excluded from further analysis due to: 1. Sensor data corrupted by large unexpected noises; 2. Hardware failure during the data acquisition. Furthermore, two TD children were excluded due to missing data from two UL kinematic data during evaluation with REAplan.

Strategy of feature extraction and selection

Kinematic parameters

UL kinematics were computed from each task. For the Free Amplitude task, the smoothness, speed and straightness indices were computed. For the Target task, an inaccuracy index was added. For the Square and Circle tasks, the speed, inaccuracy and smoothness indices were computed.

EMG and IMU-ACC features

sEMG and IMU-ACC data were collected from wearable sensors (Trigno, Delsys Inc., Natick, MA, USA). Each sensor included information from both muscle activation, via surface EMG sensors, and position by triaxial ACC. Eight sensors were attached to the surface of the skin of the anterior deltoid, lateral deltoid, posterior deltoid, biceps brachii, triceps brachii, infraspinatus, brachialis and brachioradialis, according to the guidelines of the SENIAM project [27]. Forty sEMG features and six IMU-ACC features were extracted from each EMG segment and accelerometer signal. More details about the feature extraction method used in this paper could be found in the author's recently published

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classification model for the assessment of UL motor function using data from EMG and IMU-ACC presented in [28].

Feature selection

From our previous study [28], the best accuracy to differentiate between TD children and children with CP pre- and post-Robot-AT was obtained during the circle task. Each child had to draw a circle with a 4-cm radius using REAplan. Thus, in the current study only UL kinematics from the circle task will be analyzed. Consequently, a total of 12 extracted features were used for further analysis. The Kaiser-Meyer-Olkin (KMO) measure was used to reduce the set of 12 features in preparation for factor analysis. Bartlett Test of Sphericity at 426.158, p = 0.000 and KMO=0.87 indicated that the data were appropriate for the purpose of PCA. From the 12 features, only the velocity did not meet the criteria of measurement of sampling adequacy (=>0.50). 11 features were then included: inaccuracy, smoothness, Spectral Moment 2 (SM2), Integrated EMG (IEMG), Average Amplitude Change (AAC), Zero Crossing (ZC), Multiple Hamming Window (MHW), the fourth Coefficient of Cepstral Analysis (CC4), Maximum Fractal Length (MFL), Mean Spike Slope (MSS) and the mean of the magnitude of acceleration (mean IMU-ACC).

Data analysis

Calculation of similarity indices

Among all extracted features, eight EMG and one IMU-ACC features provided enough information to distinguish between healthy children and children with CP pre-robot-AT and post-robot-AT [28]. Each EMG and IMU-ACC feature can be arranged as an 8-element vector for all channels. For each feature vector, we first calculated the Euclidean distances between any given CP child α and all TD children. Then we selected the maximal distance as a similarity index which can be described as follows:

$$d^{\alpha,TD}=\max\left(\left\|c^{\alpha}-c^{\beta_j}\right\|\right) \quad (1)$$

where:

c refers to a feature vector

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α refers to a CP child

β_j refer to TD child; $j = \{1, .., n\}$, n is the sample size of TD children.

The minimal distance was used instead of the maximal distance to produce similarity indices for each TD child with respect to the normal reference.

ULMFI generation

Principal Component Analysis (PCA) [29] was conducted to reduce the feature set into a set of principal dimensions while preserving as much information as possible. Since the principal component transformation is not scale invariant, each variable was normalized by subtracting the mean and dividing by the standard deviation using the TD group. We calculated the ULMFI using a distance metric similar to the GDI [25]. The m retained principal components were then considered as a data sample matrix with each row representing an m-dimensional feature vector for each subject. Here, the purpose of the PCA was not the reduction of the feature space but rather transforming the original possibly correlated features into a simpler data set with unrelated variables. The new components will be used to define the ULMFI score and avoid any overlap between the original parameters used to compute the deviation from the TD group.

Given the Euclidean distance between a CP subject α and the average TD group, the raw ULMFI for subject α is defined as:

$$\mathrm{ULMFI}_{\mathrm{raw}}^{\alpha} = \ln(\mathrm{d}^{\alpha,\mathrm{TD}}) \quad (2)$$

Where $\mathrm{d}^{\alpha,\mathrm{TD}} = \left\| \mathrm{c}^{\alpha} - \mathrm{c}^{\overline{\mathrm{TD}}} \right\|$; $\mathrm{c}^{\overline{\mathrm{TD}}}$ is the average feature component vector of the TD group.

For clinical interpretation purposes [30], the ULMFI for each CP child α was transformed to a scaled version of the TD group (Mean (SD); 100 (10)) as follows:

$$\mathrm{zULMFI}_{\mathrm{raw}}^{\alpha} = \frac{\mathrm{ULMFI}_{\mathrm{raw}}^{\alpha} - \mathrm{Mean}(\mathrm{ULMFI}_{\mathrm{raw}}^{\mathrm{TD}})}{\mathrm{SD}(\mathrm{ULMFI}_{\mathrm{raw}}^{\mathrm{TD}})} \quad (3)$$

$$\mathrm{ULMFI}^{\alpha} = 100 - 10 \times \mathrm{zULMFI}_{\mathrm{raw}}^{\alpha} \quad (4)$$

Where $\mathrm{ULMFI}_{\mathrm{raw}}^{\mathrm{TD}}$ is the raw ULMFI for each subject in TD group.

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Validity

The concurrent validity of the ULMFI was evaluated by examining its behavior with respect to clinical scales: BBT and FTN tests. The discriminative validity of ULMFI in CP children pre- and post-Robot-AT and TD group was investigated with Kruskal Wallis, Mann-Whitney and paired Wilcoxon tests with Bonferroni correction, by use of kinematic, EMG and IMU-ACC measurements. All statistical analyses were performed using R Statistical Software (version 3.6.1; R Foundation for Statistical Computing platform).

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Results

At first, we will present results for feature reduction using PCA. Then, differences in ULMFI between TD children and children with CP pre- and post-Robot-AT will be illustrated. Finally, we will show whether there were significant changes in kinematic and EMG activity in the UL post-Robot-AT.

After performing PCA, when load attributes of the 11 features, the first six components explaining more than 98 percent of the total variance were retained for further analysis. Results for analysis are represented using graph of PCA with the first two dimensions (Figure 1 (a)).

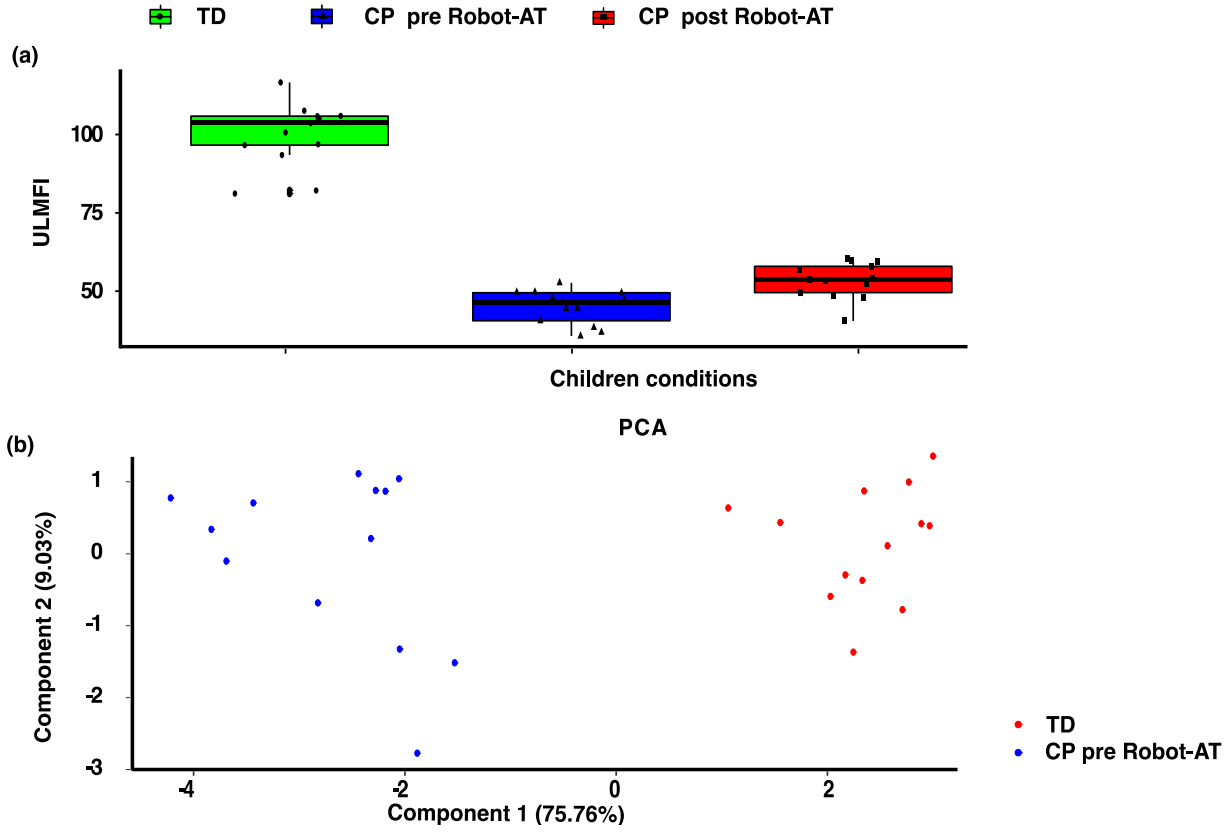

Figure 1 (a) Comparison of the Upper Limb Motor Function Index between Typically Developing (TD) children, children with cerebral palsy pre-Robot-Assisted Therapy; (b) Sample representation using the first two components from Principal Component Analysis (PCA).

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PCA clearly separates TD and CP groups. The six retained components were then employed to generate ULMFI for CP children pre-Robot-AT and TD children. ULMFI for CP children post-Robot-AT were predicted using the loading matrix of PCA. Pairwise comparisons using Wilcoxon rank sum test revealed significant differences (p<0.001). Figure 1 (b) shows the mean ULMFI for TD children (mean (SD), 100 (10)) and pre–post changes for CP children (44.9 (5.43) and 53.4 (5.73), for CP pre- and post-Robot-AT respectively). The ULMFI improved significantly after Robot-AT. Boxplots in Figure 2 show a distinction between the TD and CP groups, with a closer mean value for each feature in the CP group post-Robot-AT to those of TD group.

For all EMG and IMU-ACC features, the Kruskal Wallis test revealed significant differences between groups. Results are presented in Table 2 and Figure 2, only features with large effect size will be discussed [31] (r=>0.5). Results for smoothness and inaccuracy variables are shown in Table 3.

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Table 2 Significant group difference according to the Mann-Whitney U and paired Wilcoxon tests, accompanied with effect sizes r. Only features with significant differences between the comparing groups are reported. Variable definitions are reported in [28].

	TD vs CP children pre-Robot-AT				
Feature	Muscle	Mean	Mean	*p*	*r*
SM2	Biceps	0.02 (0.03)	0.46 (0.79)	0.010	0.50
	Infraspinatus	0.04 (0.02)	0.19 (0.32)	0.031	0.42
	Triceps	0.02 (0.01)	0.27 (0.49)	0.031	0.42
IEMG	Biceps	0.38 (0.30)	1.69 (2.01)	0.008	0.51
ACC	Lateral deltoid	0.96 (0.01)	0.94 (0.01)	0.013	0.48
	Brachialis	0.95 (0.02)	0.92 (0.03)	0.021	0.45
	Posterior deltoid	1.13 (0.04)	1.02 (0.07)	<0.001	0.75
AAC	Biceps	4.40 (3.09)	22.68 (26.12)	0.016	0.47
	Infraspinatus	7.32 (1.71)	13.90 (8.06)	0.010	0.50
	Triceps	5.89 (2.00)	17.36 (17.74)	0.045	0.39
	Anterior deltoid	9.15 (5.88)	19.93 (14.22)	0.022	0.45
MHW	Biceps	1.18 (2.40)	45.28 (79.84)	0.007	0.53
	Triceps	1.12 (0.81)	55.43 (15.78)	0.029	0.43
	Brachioradialis	4.25 (5.50)	18.48 (25.10)	0.044	0.39
MFL	Biceps	-5.80 (0.41)	-4.79 (1.10)	0.012	0.49
	Infraspinatus	-5.25 (0.21)	-4.81 (0.55)	0.031	0.42
	Triceps	-5.51 (0.29)	-4.91 (0.77)	0.031	0.42
	TD vs CP children post-Robot-AT				
SM2	Biceps	0.02 (0.03)	0.11 (0.26)	0.031	0.42
	Brachialis	0.02 (0.01)	0.06 (0.07)	0.021	0.45
IEMG	Brachialis	0.38 (0.21)	0.67 (0.35)	0.035	0.41
ACC	Infraspinatus	0.87 (0.05)	0.97 (0.10)	0.022	0.45
	Brachioradialis	0.95 (0.04)	0.98 (0.02)	0.034	0.41
	Posterior deltoid	1.13 (0.04)	1.13 (0.13)	0.019	0.46
MHW	Biceps	1.18 (2.40)	5.95 (9.56)	0.018	0.46
MFL	Biceps	-5.80 (0.41)	-5.30 (0.69)	0.031	0.42
	Brachialis	-5.57 (0.67)	-4.88 (1.18)	0.016	0.47
	CP children pre_Robot-AT vs CP children post-Robot-AT				
SM2	Biceps	0.46 (0.79)	0.11 (0.26)	0.021	0.45
	Anterior deltoid	0.40 (0.56)	0.07 (0.08)	0.048	0.39
ACC	Infraspinatus	0.93 (0.08)	0.97 (0.10)	0.014	0.48
	Anterior deltoid	1.00 (0.10)	1.10 (0.03)	0.006	0.54
	Posterior deltoid	1.02 (0.07)	1.13 (0.13)	0.008	0.52
AAC	Biceps	22.68 (26.12)	8.06 (8.16)	0.040	0.40
	Anterior deltoid	19.93 (14.22)	10.01 (5.89)	0.010	0.50
MHW	Anterior deltoid	79.28 (17.32)	3.38 (3.22)	0.040	0.40
MFL	Biceps	-4.79 (1.10)	-5.30 (0.69)	0.048	0.39
	Brachialis	-5.29 (0.76)	-4.88 (1.18)	0.040	0.40
	Anterior deltoid	-4.59 (0.68)	-5.03 (0.43)	0.017	0.47

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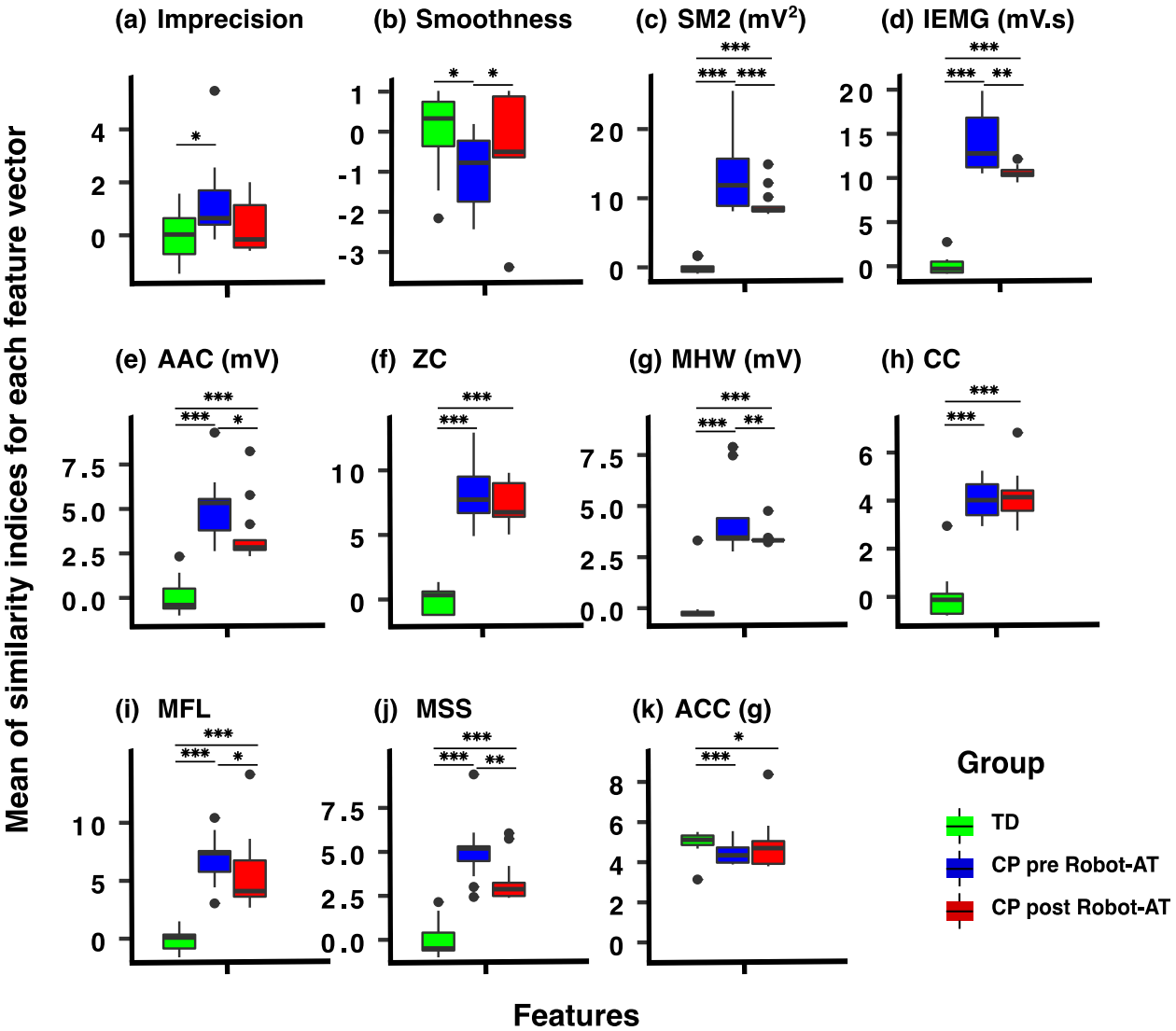
CC4	Infraspinatus	0.41 (0.08)	0.33 (0.10)	0.048	0.39

Bonferroni-corrected p-values are reported. Bold type indicates large effect size (=>0.50). TD, Typically Developing; CP pre-Robot-AT, children with cerebral palsy pre-Robot-Assisted Therapy; CP post-Robot-AT, children with cerebral palsy post-Robot-Assisted Therapy; AAC and **MHW** are in [uV].

Figure 2 Boxplots of similarity indices for kinematic, EMG and IMU-ACC parameters



for Typically Developing (TD) children, children with cerebral palsy pre-Robot-Assisted Therapy (CP pre-Robot-AT) and CP post-Robot-AT (children with cerebral palsy post-Robot-Assisted Therapy. Variable definitions are reported in [28].

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Table 3 Significant group difference according to the Mann-Whitney U and paired Wilcoxon tests, accompanied with effect sizes r for smoothness and inaccuracy variables.

TD vs CP children pre-Robot-AT				
Variable	Mean	Mean	*p*	*r*
Smoothness	0.68 (0.07)	0.61 (0.06)	0.010	0.49
Inaccuracy	0.52 (0.16)	0.72 (0.24)	0.020	0.46
TD vs CP children post-Robot-AT				
Smoothness	0.68 (0.07)	0.66 (0.09)	0.661	0.09
Inaccuracy	0.52 (0.16)	0.56 (0.15)	0.540	0.12
CP children pre_Robot-AT vs CP children post-Robot-AT				
Smoothness	0.61 (0.06)	0.66 (0.09)	0.054	0.37
Inaccuracy	0.72 (0.24)	0.56 (0.15)	0.033	0.42

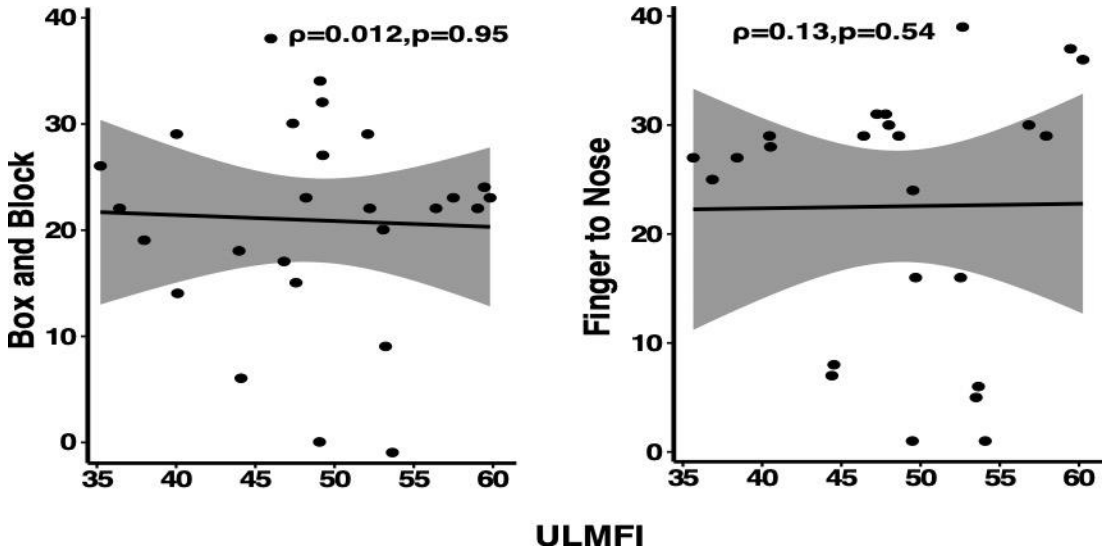

Figure 3 Spearman's rank correlation (ρ) between clinical tests and Upper Limb Motor Function Index (ULMFI).

For CP group pre- and post-Robot-AT, Figure 3 shows a weak but a positive correlation between ULMFI and clinical tests (ρ=0.012, p=0.95 and ρ=0.13, p= 0.54 for BBT and FTN respectively). Wilcoxon rank sum test revealed significant differences before and after Robot-AT for FTN (p=0.03) but not for BBT (p=0.57).

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Discussion

The aim of this study was to assess the effectiveness of Robot-AT in children with CP using a quantitative ULMFI. The ULMFI was developed using a distance metric similar to the GDI [25]. The discriminative validity of the ULMFI was established in CP children pre-Robot-AT and TD group by use of kinematic, EMG and IMU-ACC variables. The concurrent validity was determined by comparing the ULMFI to clinical assessments in CP children pre- and post-Robot-AT.

The ULMFI was developed based on two kinematic parameters from the REAplan, eight EMG features and mean IMU-ACC. In our recent study, the eight EMG features were the top ranked features among each category of sEMG features. Moreover, adding mean IMU-ACC provided the best classification accuracy in distinguishing TD, children with CP pre- and post-Robot-AT during the circle task [28]. The results support our hypothesis that Robot-AT would increase ULMFI values in children with CP and that levels of muscle activation would be closer to those of TD children (Figure 1 (b)) and Figure 2). These findings are in accordance with recent studies that reported that Robot-AT offers a great improvement in UL motor function and could be considered as a promising intervention for children with CP [6, 18, 21].

Results reported Figure 2 and Table 2 showed that some parameters appear to have a great potential in distinguishing between CP and TD children. The posterior deltoid muscle showed higher mean IMU-ACC values for TD group and CP post-Robot-AT in comparison to CP pre-Robot-AT (Table 2). The decreased mean IMU-ACC may be caused by poor selective motor control [32] during shoulder horizontal extension for circle task. Several studies proved that this parameter can be improved with rehabilitation therapies [33, 34], which is the case for CP children post-Robot-AT in the current study.

Results on the significance of differences between healthy and pathological muscles showed a general trend of higher values in the biceps and infraspinatus muscles for the SM2, IEMG, AAC and MHW parameters in CP group (Figure 2 (c), (d), (e) and (g) respectively). This is consistent with the necessity of the activation of the elbow and shoulder muscles to perform the extension/flexion and external rotation movements of the shoulder during the circle task. SM2 feature was different in triceps and infraspinatus

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muscles as well, with higher activation in pre-Robot-AT group. This is in accordance with Prosser et al. [35] who reported high values of the time-frequency domain features in all muscles for the CP group during gait cycle. For CP group, AAC exhibited higher values in infraspinatus, triceps and anterior deltoid muscles than TD group. For MHW, higher activation was observed in biceps, triceps and brachioradialis muscles in pre-Robot-AT group. The results of the paired difference tests suggest that there is more MU (Motor Unit) recruitment in pathological muscles compared to healthy muscles, in terms of signal energy, multi-window and information complexity of the EMG signals.

There was a general trend showing a higher mean IMU-ACC in anterior and posterior deltoid muscles and lower AAC in biceps muscle for children post-Robot-AT. The AAC feature is similar to the waveform length (WL) feature but averages the WL over the time segment. This feature provides information on the waveform complexity in each segment and indicates the degree of variations in EMG signals [36]. Increase in EMG signal complexity as seen by AAC indicates increase in activation level of the muscles. Results indicate that higher levels of activation of EMG features were detected in CP pre-Robot-AT compared to TD group [37]. Neurological damage in children with CP results in recruiting a higher number of motor units and the need to stabilize the joints, to achieve the same movement as the TD group [38]. This is in agreement with Haddara et al. [39] who found that time-domain metrics were higher in patients recovering from MSK elbow trauma versus the healthy population. The results of this study suggested that children in pre-Robot-AT have progressed in their therapy. This was particularly seen in the mean IMU-ACC of the anterior and posterior deltoid muscles, and the AAC of the anterior deltoid muscle activity, which tended to be similar to those of TD children.

A further finding in this research study was the improved smoothness after Robot-AT (Figure 2 (b)), which is similar to the observations made by several recent studies [5, 6, 18].

The ULMFI exhibited a non-significant but a positive correlation with BBT and FTN (Figure 3). This positive correlation may explain the proximal motor control of the UL, involved in BBT and FTN. The poor correlation observed in this study may be partly due to the relatively small sample size or to the fact that kinematic, EMG and IMU-ACC

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measurements are able to detect specific changes in UL motor function after intervention that conventional scales could not quantify. Motor function improved after Robot-AT according to FTN which is consistent with the improved EMG and the mean IMU-ACC parameters for the proximal muscles that controls the shoulder [40]. However, other clinical assessments may be more appropriate and should be administrated to depict a real improvement in these muscles, such as the proximal upper limb section in the FMA.

We propose the ULMFI as a quantitative assessment for children with CP after Robot-AT. Higher activation in proximal muscles around the shoulder could be due to the increased MU recruitment and a compensatory movement strategy. CP children post-Robot-AT tended to exhibit kinematic, EMG and IMU-ACC signals closer to those of TD group.

One limitation of this study was the relatively small sample size (n=26) which may affect the reliability of statistical results. Due to this small sample, the parametric assumptions were not met. Therefore, nonparametric tests were carried out instead of parametric tests. Future studies may therefore include a larger sample of CP children to validate the quantitative assessment index proposed in this study. Another consideration is that all tasks in the evaluation process are made in a small workspace without regard to the patient's specific characteristics and abilities. In this context, evaluation tasks may be less relevant, and results may be misleading. A patient-specific evaluation task and an individualized trajectory should be designed for the REAplan.

Conclusion

The objective of this study was to develop an index for quantitative assessment of the upper limb motor function in children with cerebral palsy before and after intervention using the REAplan.

The main results showed that the ULMFI was higher in children with cerebral palsy post therapy ($p<0.001$). FTN values improved after therapy ($p<0.03$). A weak but positive correlation was observed between ULMFI and clinical tests ($\rho=0.012$, $p=0.95$ and $\rho=0.13$, $p= 0.54$ for BBT and FTN respectively).

 doi:10.20944/preprints202001.0021.v1

These results showed that the ULMFI could successfully differentiate between the typically developing group and children with cerebral palsy and was effective in assessing the improvement of upper limb motor function post therapy.

The ULMFI could be extended to assess and monitor rehabilitation therapies of other populations, such as those with stroke and Parkinson's disease.

Acknowledgments

We gratefully acknowledge the contribution of the Canada Foundation for Innovation (CFI). The authors would like to thank the patients who participated in this study as well as the occupational therapists' team at "École Victor-Doré" for their collaboration.

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 doi:10.20944/preprints202001.0021.v1