Upper Limb Functional Assessment of Children with Cerebral Palsy Using a Sorting Box

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Abstract— **We investigated the use of a sorting box to obtain a quantitative assessment of upper limb motor function in children with cerebral palsy. In our study, children with and without cerebral palsy placed and removed geometrical objects of a sorting-box while their wrist position was monitored by a camera-based, motion-tracking system. We analyzed three different smoothness metrics (logarithmic dimensionless jerk, spectral arc-length and number of peaks) together with time to task completion. Our results suggest that smoothness metrics are an effective tool to distinguish between impaired and non-impaired subjects, as well as to quantify differences between the affected and less-affected sides in children with hemiparetic cerebral palsy.**

I. Introduction

Cerebral Palsy (CP) refers to a group of permanent disorders of the development, movement and posture that is caused by non-progressive disturbances that occur during brain development of the fetus or child up to 3 years old, or as a result of a Central Nervous System Injury [1]. Impairments caused by CP include motor, sensory, perceptual, cognitive and communication disturbances, as well as epilepsy. Its global impact is 2 to 2.5 cases per 1000 children born [2], with spastic hemiparesis being the predominant type of CP in the world [3]. UNICEF estimates that 80% of people with motor disabilities live in developing countries [4]. In Mexico, the Ministry of Health reports that the ninth cause of attention in the Integral Family Development National System (SNDIF) is CP, in addition to a rate of 3 cases per 10,000 infants with spastic hemiparesis [1].

Because of the previous indicators and the frequent use of the upper limb in daily life activities [2], it is important to consider efficient ways to assess the functional capacity of a patient. However, up to now, there is no general consensus on what the best procedures for upper limb functional assessment are [5].

One way to obtain an upper limb assessment is by recording specific movements and computing specific metrics, in order to quantify a measurement of interest [6]. One of the most commonly used methods to record and analyze human movements are motion capture systems, which use video and/or infrared cameras in order to create a digital model of any movement, using reflective markers and photogrammetry [7-9]. Jaspers et al. [5] performed a review of the studies that focus on obtaining objective measurements of the upper limb movement in children with CP, and found that 100% of the elected articles used motion capture.

Besides the technical limitations of developing valid, reliable and sensitive metrics for functional assessment, assessment of children poses significant practical challenges. Some of these challenges include keeping the child's attention during the whole assessment procedure and deliver easy-to-understand instructions. In this paper, we propose the use of the sorting box developed in [10] as a method to perform a functional assessment task. The use of a sorting-box keeps the children engaged with the activity and allows for systematic categorization of movements.

In our experiments, children with and without CP were asked to pick different geometrical objects from a container and place them in a sorting box, and vice versa from sorting-box to a container. We analyzed: *i*) the performance by computing the time to complete the task, and *ii*) the quality of the movements by computing different smoothness metrics presented in [11]. Our results suggest that smoothness metrics are sensitive enough to distinguish motor impairments.

II. Methodology

A. Subjects

Twelve children (between 6 and 12 years old) participated in the study. Nine children (six female) without history of neurological impairments composed the *control group*, while three children diagnosed with hemiparetic cerebral palsy (one female) composed the *testing group*. Experiments were performed at the Motion Analysis Laboratory at the *Centro de Rehabilitación Infantil Teleton*, Estado de Mexico (CRIT), Mexico. The study was approved by the ethics committee of CRIT. Parental consent was obtained prior to participation.

B. Procedure

Children were seated in front of a sensorized sorting box [10]. The sorting box consists of a square-shaped aluminum container with a nylon cover, where four wooden blocks are inserted; above each figure hole, a switch is used to identify if the blocks have been inserted. Along with the sorting box, a container is used to hold the blocks; at its lateral ends, two green buttons are placed in order to identify the beginning and ending of task. The wooden blocks are an orange cylinder, a blue rectangular parallelepiped, a green rectangular parallelepiped and a red triangular prism as

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shown in Fig. 1. Children were seated in a fixed height chair (0.6 m from the floor) and the sorting box was placed on a small desk (0.8 m above the floor). A six-camera motion tracking system (BTS SMART-D) was used to track a reflective marker placed on the subject's wrist at 140Hz.

Initial position was seated in front of the sorting block box, arms relaxed, with both hands pressing both green buttons as shown in Fig. 1. When instructed, the child had to use one hand to reach for a wooden block in the container and place it in its corresponding place in the sorting box (sub-task I - filling, pick-and-place) and return the hand to the initial position (sub-task II - filling, return). After a period of 5 seconds, the child was asked to pick and place a new object. These sub-tasks were repeated until all four objects were placed in the sorting box. Once the sorting box was filled, the procedure was repeated backwards. First, the child was asked to reach for a wooden block in the sorting box (sub-task III - unfilling, pick), place it in the container and return the hand to the initial position (sub-task IV - unfilling, place-and-return). Once this whole procedure was completed, the child was asked to do the same with the opposite hand. This resulted in a total of 16 movements that involved arm flexion and extension per experimental session. Children were asked to repeat the experimental set 2 times. Fig. 1 illustrates the first reaching movement of an experimental set, using the right arm.

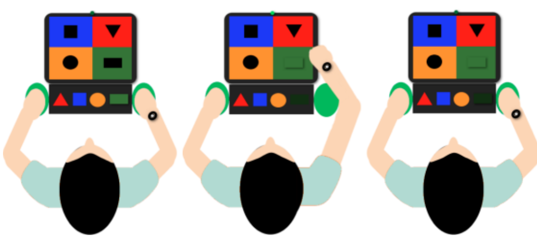

Figure 1. Filling example: initial position(left), object in board (center) and returning to the initial position (right).

C. Data analysis

Three dimensional position data of the wrist obtained by the motion tracking system was processed offline using ad-hoc code implemented in MATLAB (Mathworks, 2011). If missing data occurred due to a temporal loss of the marker, linear interpolation was performed. Data was filtered using a zero-phase digital low-pass filter (Butterworth, 12-order, cutoff frequency = 20 Hz) prior to analysis.

Using the sensors placed on the sorting box, sub-tasks I, II, III, and IV were identified and segmented. The time elapsed to complete each task, speed profiles, as well as the logarithmic dimensionless jerk metric (LDJM), peaks metric (PM) and the spectral arc-length metric (SALM) [11] were calculated using data from the second experimental attempts from the control and testing groups.

With the smoothness metrics results and completion times, the average of every sub-task (considering the 4 different wooden blocks) was contrasted between the control group and each testing subject. In order to find the existence of significant relationships between the computed metrics and completion times, Pearson's correlation coefficient was calculated, along with p-values for statistical significance.

D. Smoothness Metrics

A feature of healthy motor behavior is smooth movement, characterized by closely spaced in time submovements [11]. Equations 1-6 describe the different smoothness metrics used for this study.

SALM is defined as the negative arc length of the amplitude and frequency-normalized Fourier magnitude spectrum of the speed profile, considering a movement with a speed profile v(t) [10]:

$$\eta_{sal} \triangleq -\int_0^{\omega_c} \sqrt{\left(\frac{1}{\omega_c}\right)^2 + \left(\frac{d\hat{V}(\omega)}{d\omega}\right)^2}\, d\omega \qquad (1)$$

$$\hat{V}(\omega) \triangleq \frac{V(\omega)}{V(0)} \qquad (2)$$

Where ω_c = 20 Hz, is the frequency band that covers normal and abnormal human movements and $V(\omega)$ is the Fourier magnitude spectrum of v(t).

PM is the count of local maxima of the speed profile:

$$\eta_{pm} \triangleq -\#\{v_{maxima}\} \qquad (3)$$

$$v_{maxima} \triangleq \left\{v(t): \frac{dv}{dt} = 0 \; and \; \frac{d^2v}{dt^2} < 0\right\} \qquad (4)$$

Finally, the LDJM is defined as the negative logarithm of the total squared normalized jerk:

$$\eta_{ldj} \triangleq -ln\left(\frac{(t_2-t_1)^3}{v_{peak}^2}\int_{t1}^{t2}\left|\frac{d^2v}{dt^2}\right|^2 dt\right) \qquad (5)$$

$$v_{peak} \triangleq \max_{t\in[t1,t2]} v(t) \qquad (6)$$

III. RESULTS

Fig. 2 illustrates the speed profiles of a subject from the control group and a subject from the testing group in a pick & place task, using the right arm and the second wooden block.

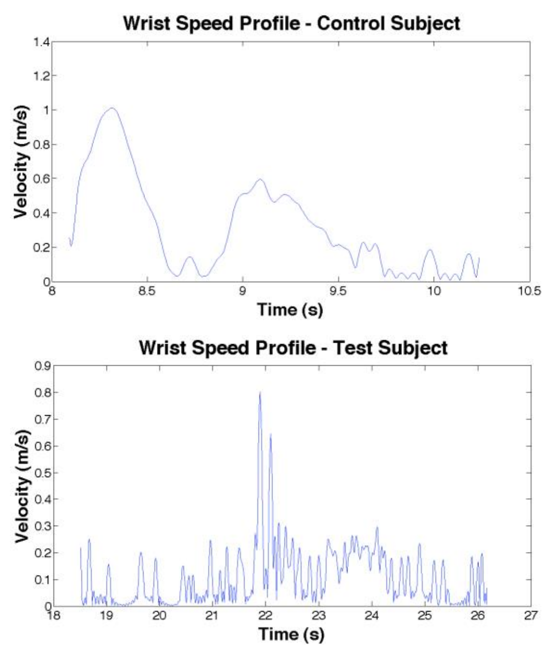

Figure 2. Wrist speed profiles for an unimpaired child (Control subject) and a child with CP (Test subject).

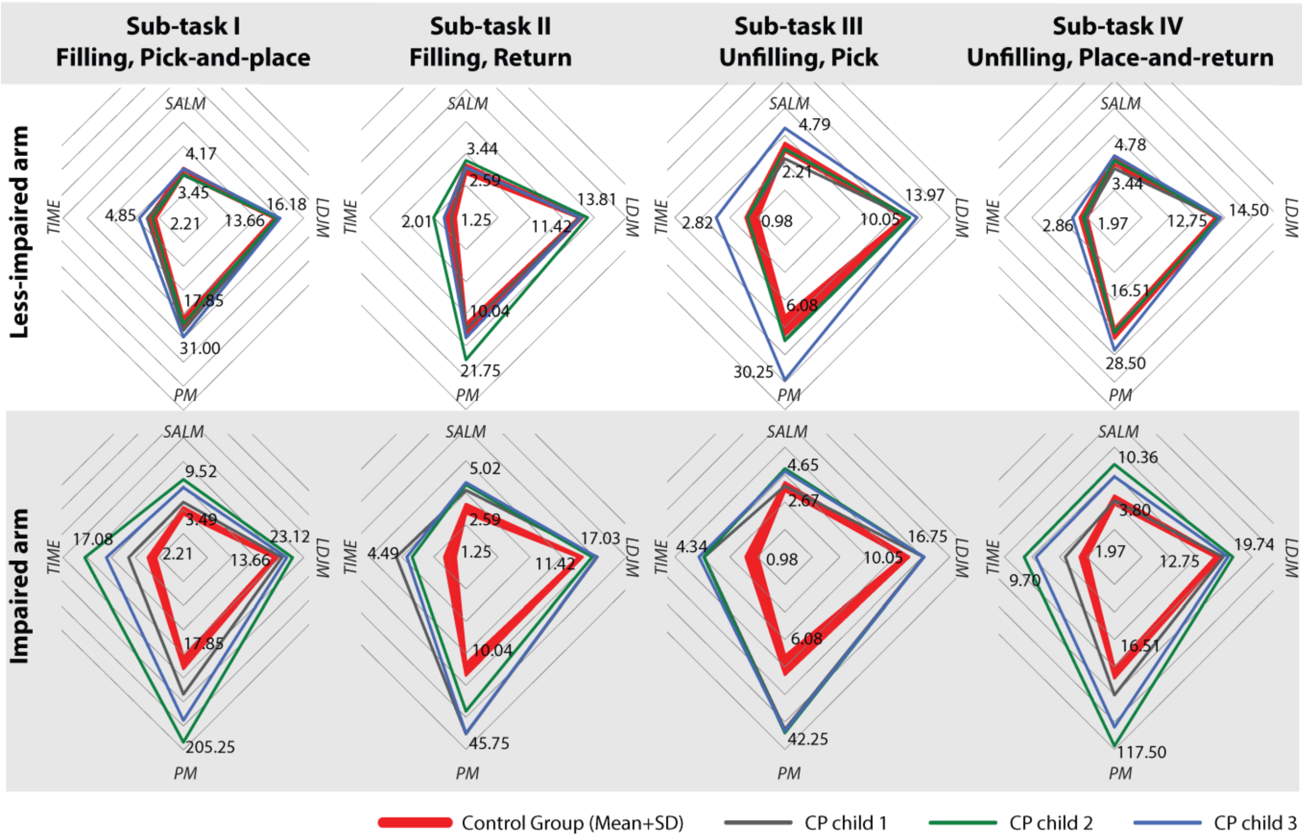

Figure 3. Metrics comparison: for sub-tasks I-IV, a contrast between each impaired individual is shown. In the upper row, results for the less impaired side of each experimental subject are contrasted to the control groups average+SD (red series). In the lower row, results for the impaired side of each experimental subject are contrasted to the control groups average+SD (red series). In this radial representation, each poligon edge is associated to a different metric (i.e. Spectral Arc-Length Metric, Logarithmic Dimensionless Jerk Metric, Peaks Metric and completion TIME).

Fig. 3 shows a comparison between the smoothness metrics and completion times, for each sub-task, comparing the average of the control group with the average of the affected and unaffected sides of each testing group subject.

For all the sub-tasks, the SALM, LDJM and PM computed values from the affected sides of the CP subjects show a greater magnitude than the average of the control group. The unaffected sides of the CP subjects resulted in a smaller magnitude for the computed metrics compared to their affected sides; however, not in every case these values are greater than the average of the control group. Hence, subjects with motor impairments show a lack of speed control of their affected upper limb, reflected in the magnitude of the computed metrics.

Completion time (shown as Time in Fig. 3), a simple but effective parameter, was also capable of differentiate between the control group average and the testing group experimental trial averages in the same way the smoothness metrics did.

Table I indicates the correlation coefficients for the computed metrics. For the control group, Pearson's correlation between SALM and LDJM/PM/Time showed a moderate/strong positive relationship; also, a strong/very strong positive relationship between LDJM and PM/Time for the control group is shown. In all cases from the control group, a very strong positive relationship between PM and Time was observed. Highly significant values were obtained for all cases ($p<0.01$). For the testing group, all the correlation coefficients were found to be strong/very strong. For all instances, highly significant values were obtained ($p<0.01$).

TABLE I. CORRELATION BETWEEN METRICS.

Comparison	**Filling (Pick & Place)**		**Filling (Return)**	
	Control Group	***Testing Group***	***Control Group***	***Testing Group***
SALM vs. LDJM	0.3628	0.8979	0.5058	0.6308
SALM vs. PM	0.3466	0.8978	0.2992	0.6854
SALM vs. Time	0.3772	0.8747	0.4255	0.6531
LDJM vs. PM	0.8614	0.9332	0.5717	0.8650
LDJM vs. Time	0.8346	0.9169	0.6483	0.8721
PM vs. Time	0.9214	0.9956	0.7729	0.9629
Comparison	**Unfilling (Pick)**		**Unfilling (Place & Return)**	
	Control Group	***Testing Group***	***Control Group***	***Testing Group***
SALM vs. LDJM	0.4089	0.5527	0.4035	0.8145
SALM vs. PM	0.3079	0.6045	0.5884	0.9228
SALM vs. Time	0.3944	0.4948	0.4890	0.9127
LDJM vs. PM	0.7524	0.9631	0.6161	0.9168
LDJM vs. Time	0.7703	0.9373	0.5712	0.9091
PM vs. Time	0.9224	0.9481	0.8846	0.9941

Correlation coefficients showed a significant link between the three smoothness metrics and the completion time, particularly the PM. For the control group, SALM presented the lowest correlation values, exposing a moderate link with the other smoothness metrics; however, a strong link is shown for the test group because of its reduced size.

IV. Discussion

Our long-term goal is to develop valid, reliable and sensitive assessments to quantify the upper limb motor functional abilities of children with cerebral palsy. In our study, we explored the use of a sorting box as means to record systematic movements in a motivating and easy-to-understand environment for children.

We analyzed the speed profiles of movements performed during the filling and unfilling of the sorting box with different geometrical objects. The smoothness of these movements was analyzed by three different metrics: SALM, LDJM and PM. These metrics resulted effective in distinguishing between non-impaired and motor impaired children. All three smoothness metrics and the time to completion metric were capable to show significant differences between the affected and unaffected sides of hemiparetic subjects. However, variances between the magnitudes of the same metrics were found. PM shows bigger magnitude differences for the same subjects when the completion time tends to increase, and when the metric is computed for the affected side of a hemiparetic subject. Both SALM and LDJM present less abrupt magnitude changes in all cases. Though, SALM has more subtle magnitude changes, compared to LDJM, because of its sensitivity, considering the different speed profiles obtained by the healthy and hemiparetic subjects.

Movement smoothness has become an effective indicator of the upper limb's function by showing the differences between healthy and impaired subjects while assessing the hand's trajectory [12], shoulder's flexion/adduction and elbow flexion [13]. Moreover, the number of peaks from a velocity profile (PM) is a commonly used metric in upper limb assessments, showing better reliability and consistency for tests which involve cerebral palsy subjects [14], than stroke subjects [15], where the SALM exposed good performance reliability.

A comparison with more impaired subjects is in progress in order to establish different degrees of neuro-motor impairments for the test subjects. Different studies [16-17] have shown a significant correlation between movement smoothness and the amount of motor impairment, measured by clinical scales. Hence, clinical assessments will be done in order to validate the proposed results and to validate smoothness measures as effective and reliable tools for the assessment of the upper limb in subjects with CP.

Our current work also involves the use of inertial sensors placed on the upper limb to replace the need of a camera-based motion tracking system. This could lead to the standardization of the sorting box as an evaluation tool that can be easily implemented in the clinical practice.

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