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RESEARCH ARTICLE

Quantitative Upper Limb Assessment With Natural User Interface in Children With Hemiparesis

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This research protocol was authorized by the parents (informed consent) and by the APAC Institute under the National Technological Institute of Mexico (TecNM)-APAC collaboration agreement (TecNM in Celaya-1-2020-247).

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Association for People with Cerebral Palsy.

ABSTRACT Quantitative, efficient, and accurate measurement of upper limb motor performance is relevant for monitoring upper limb progress in daily activities of people with cerebral palsy, which is helpful to define an appropriate rehabilitation procedure. Currently, motion capture sensors using a Natural User Interface (NUI) are the most feasible solutions due to the low-cost implementation, portability, and effectiveness for upper limb motion analysis. A quantitatively assessment study of the upper limb motor performance for children with spastic hemiparesis using the NUI Kinect v2 sensor is described in this paper. The study participants were eighteen children with an average age of 8.28 $\pm$ 2.32 years having a Manual Ability Classification System level I and II. The assessment was done for each participant before and after the application of a Modified Constrained-Induced Movement Therapy (mCIMT) applied five days a week along twelve weeks. According to obtained results significant differences ($p < 0.05$) in the Fugl-Meyer Assessment (FMA) score for motor performance in abduction movement of upper limb between the first and last sessions were quantitatively detected. The described NUI assessment method helped to quantitatively show that the applied therapy sessions were effective to improve upper extremity motor performance. Additionally, the upper limb movements motorically limited after the rehabilitation therapy were also identified. The main contribution of the described NUI assessment method is its potential use as a quantitative measurement tool, which might be used by specialists to objectively diagnose and consequently define an appropriate rehabilitation therapy for patients with hemiparesis.

INDEX TERMS Assessment, cerebral palsy, Kinect v2, movement, system, therapy, upper limb.

I. INTRODUCTION

The rehabilitation process of children with cerebral palsy aims to improve motor skills in daily activities and participatory integration in social life [1], [2]. Quantitative, efficient, and accurate measurement of upper limb motor performance is relevant to monitoring upper limb progress or regression in daily activities of people with cerebral palsy, which is helpful to define and improve the specifications of an appropriate rehabilitation procedure.

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In this context, the Constraint-Induced Movement Therapy (CIMT) is a commonly used procedure for upper limbs rehabilitation, where the unaffected upper limb is immobilized and the affected limb activity is notably increased by performing daily activities or intensive motor trainings [3], [4]. This technique has been shown to improve manual motor skills in children with hemiparetic cerebral palsy [4], [5]. On the other hand, the Modified Constraint-Induced Movement Therapy (mCIMT) is an alternative treatment option, where only the type of restriction, the session hours per day and the therapy duration are different [4].

The mCIMT effectiveness has been supported by several reported studies in both stroke and cerebral palsy patients. A significant improvement of upper limb motor function for hemiparesis patients is concluded in the mCIMT intervention critical review reported by Cao & Li [6].

In Yadav, et al. [7] a significant improvement in motor performance efficacy according to Fugl-Meyer Assessment (FMA) score was achieved when comparing the obtained results in one and three months ($p < 0.001$) along an mCIMT intervention in three-hours session per day to hemiparetic upper limp in stroke patients. The mCIMT validity was also assessed by Singh and Pradhan [8] with a ten-hours session per day along two weeks in forty stroke subjects. After the rehabilitation therapy, significant improvements in FMA motor performance scores were found. The authors concluded that the application of the mCIMT is an effective rehabilitation treatment for improving upper limb motor functions. Regarding to CIMT application and quantitative assessment, the use of an eight-camera motion capture system (Qualisys Ochs 400+, Qualisys, Göteborg, Sweden) was reported by authors Hansen, et al. [9], where thirty-two 12 mm markers were tracked through the Track Manager system (Version 2.15, Qualisys, Göteborg, Sweden). The shoulder function of thirty-seven stroke patients was assessed before and after the CIMT application. An improvement in a minimal upward rotational movement of less than 1° from pre- to post-CMIT was reported by the authors. However, significant upper limb movements changes were not reflected by the 3D kinematic measurements.

Concerning the application of mCIMT in patients with cerebral palsy, a comparison of the mCIMT and bimanual training effects was done by Bingöl and Günel [10], where the evaluations were performed before and after the use of qualitative scales and a dynamometer. Significant improvements were reported by the authors ($p < 0.001$), in a sample of thirty-two children with cerebral palsy, after applying a two-and-a-half hours mCIMT session per day, three days a week along teen weeks.

The low-cost sensor Kinect system can be considered an NUI because the data acquisition is performed by the Kinect v2 sensor, and the human positions and gestures are computed through a vector data processing with a markless human pose estimation algorithm. The Kinect v2 NUI system reliability has been evaluated for upper limb analysis by several researchers, where significant measurement accuracy has been found [11], [12], [13], [14], [15], [16]. In addition, the Kinect sensor NUI has been used for the clinical setting in FMA testing and kinematic variables measurements [17], [18], [19], [20], [21], [22]. The shoulder flexion and extension movements of six children with cerebral palsy were assessed through Kinect-acquired and Matlab processed data in Daoud, et al. [23]. Automatic assessment of arm flexion and extension movements along a game-based rehabilitation process in children with cerebral palsy was accomplished by the computerized assessment method.

A quantitative assessment study of the upper limb motor performance for children with spastic hemiparesis using the NUI Kinect v2 system is described in this paper. The main objective is focused on motor performance assessment before and after the mCIMT intervention using the already reported Kinect v2 assisted semi-automated method [21] in or der to quantitatively determine the progress and effectiveness of the mCIMT along the rehabilitation therapy.

II. MATERIALS AND METHODS

A quantitative experimental study using a low-cost NUI system [21] for assessing upper limb motor performance in children before and after mCIMT was conducted.

A. PARTICIPANTS

The study participants were 18 children with an average age of 8.28 ± 2.32 years. However, four dropped out the study protocol during the rehabilitation process. The study was conducted at the facilities of Association for People with Cerebral Palsy (APAC). This non-profit institution provides specialized comprehensive rehabilitation care for children and young people with cerebral palsy in Celaya, Gto. México.

The selected participants' age range was 4 up to 12 years old, because according to clinical practice and the suggestion of neurology and rehabilitation specialists, participants within this age range show significant motor performance progress in short rehabilitation time. Cognitively, participants had an average visuomotor age of 5.22 ± 2.44 years (Bender Koppitz Test [24]) to follow up the given assessment protocol. The Manual Ability Classification System (MACS) [25], levels I and II, and the Gross Motor Function Classification System (GMFCS) [25], levels I and II, were also considered participant selection criteria in this study. The MACS is related to fine motor skills, the main difference between level I and II is the quality/speed to manipulate objects. The GMFCS levels I and II indicate gross motor functions involving movements such as walking and sitting.

The study group included MACS and GMFCS levels I and II because such capabilities do not interfere with the upper limb measurements required in the mCIMT rehabilitation procedure. Participants without, or with more than six months ago, botulinum toxin application were included in the study. The following cases were excluded in the study: participants with visual, hearing, and severe cognitive impairment, participants without authorized informed consent, participants with

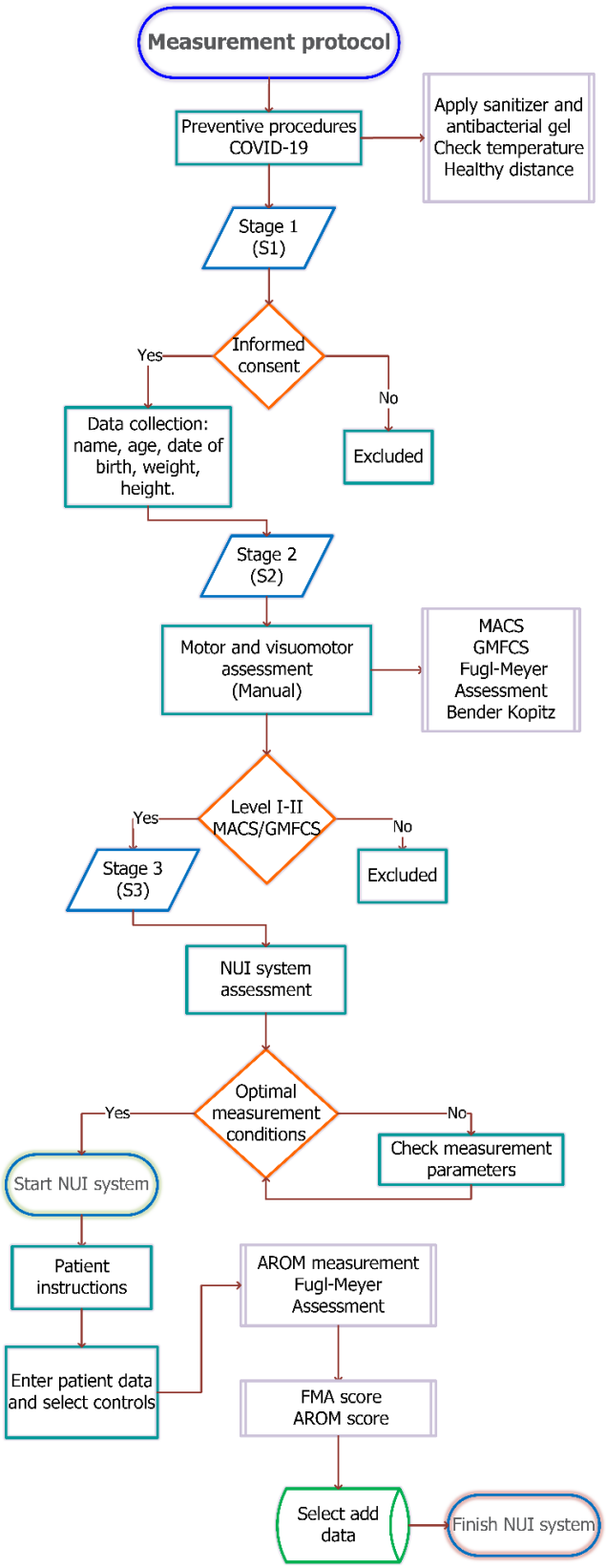

FIGURE 1. Measurement protocol flow chart.

general ailments and undergoing pharmacological or medical treatment and participants with musculoskeletal injuries.

B. MEASUREMENT PROTOCOL

The measurement protocol flow chart is shown in Figure 1. In the first study stage (S1) the assessment protocol and rehabilitation procedure information were provided to the participants' guardians, who all of them gave the signed informed consent. Preventive procedures and recommendations were carefully followed to avoid COVID-19 spread among the study participants, such as sanitizer and antibacterial gel application, temperature checking, and keeping healthy distance.

In order to determine if the participants were able to follow the required indications in the NUI assessment process, and be included in the study, each participant's cognitive level was evaluated by a psychologist through the Bender Kopitz Visuomotor Scale test [24] in second stage (S2). According to the psychologist's suggestion, participants with mental age deficits capable to follow indications were included in the study. This was done because for most participants, the resulted chronological age mismatch was due to hand manipulation when the testing was applied. The upper limb motor performance of each participant was FMA evaluated in the third study stage (S3) through the NUI system before the mCIMT intervention (Figure 2). Each participant's manual skills functionality was also evaluated in the study second stage by a physiotherapist through the MACS test [25].

In the intervention stage participants were under treatment with conventional therapy and mCIMT. The upper limb motor performance of each participant was again FMA evaluated through the NUI system after the mCIMT intervention. In this sense the progress of the mobility for each participant was assessed and determined by an NUI analysis.

The measurements obtained before and after the mCIMT are summarized in Table 1. It is worth mentioning that out of a sample of 18 participants four dropped out after the third study stage (P1, P4, P10, and P17), whose post mCIMT score is denoted as 0, and 14 finished the whole assessment study.

C. LOW-COST NUI SYSTEM

The measurement system is integrated by a low-cost Kinect v2 sensor and an HP Intel®Core™i7-9750H 9750H 2.60 GHz laptop with NVIDIA GeForce GTX 1650 graphics card [21]. The participant remained seated in front of the Kinect v2 sensor, at a two-meter distance, along the NUI assessment procedure performing voluntary movements within the flexor synergies according to the FMA scale [26]. The measurement conditions were the same as the reported ones in [21].

Essential participant data such as name and age are registered in the Graphical User Interface (GUI) (Figure 3). The participant's movements that cannot be detected by the sensor are manually recorded by the therapist through the available GUI control options, e.g., arm rotation or hand and wrist movements. However, abduction, adduction, flexion, and extension movements, corresponding to the "Volitional movement within synergies, without gravitational help" sec-

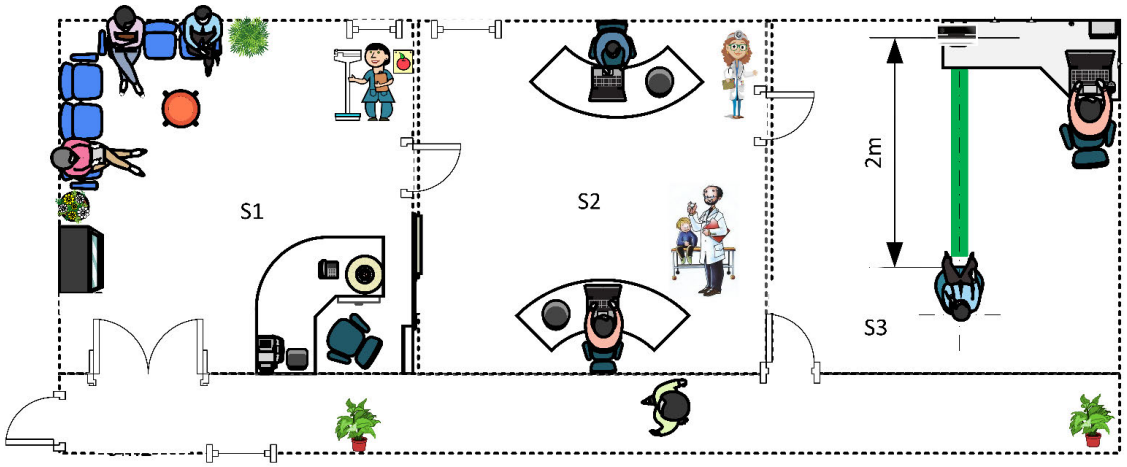

FIGURE 2. Study stages: S1- assessment protocol and rehabilitation procedure information, S2- evaluation of cognitive level and MACS upper limb motor performance, S3- assessment of upper limb motor performance through the NUI system.

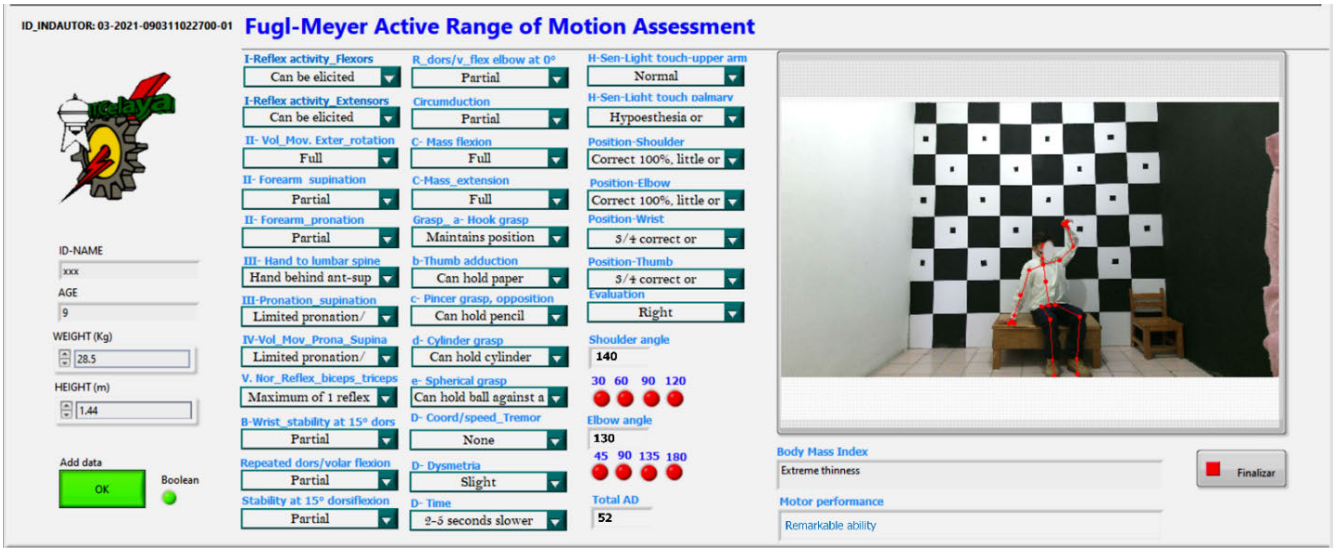

FIGURE 3. GUI of the NUI assessment system.

tion of the FMA scale can be automatically registered by the sensor.

Each score achieved by the participant in all performed activities are added in a manual FMA test e.g., active range of motion and type of grip, where the score value range is from 0 up to 3. The automated NUI assessment system follows up the manual FMA test algorithm based on both the angular Kinect acquisition and manually recorded data, by the physiotherapist, in the GUI. The NUI assessment system requires the clinician intervention only to start the angular data acquisition and to manually enter some activities scores that are not possible to be captured through the Kinect v2. The angular measurement angles were validated with a universal goniometer and previously reported work [21].

The FMA score is given by the label ''Total AD'' and the motor performance by the legends 0 to 22 for no motor ability, 23 to 31 low ability, 32 to 47 limited ability, 48 to 52 remarkable ability, and 53 to 66 as the highest score for total motor performance ability. The assessed participant's limb side is registered by the physiotherapist in the GUI as left or right. For example, the participant's right arm is evaluated by the therapist in the case shown in Figure 2. The maximum abduction movement is up to 140 for this participant and his motor performance is FMA scored as remarkable, but he is not able to adequately perform wrist movements.

D. mCITM PROTOCOL

The constraint of the healthy hand was applied for two hours a day, five days a week, along twelve weeks. The healthy side was restricted with a 15 cm bandage (depending on the participant's hand). The rehabilitation process was carried out during the confinement of COVID-19. The right way to apply

TABLE 1. Characteristics of the study population.

P	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
									Pre mCIMT									
CA	4	5	5	6	6	8	8	8	9	9	9	9	9	9	10	11	12	12
MA	-	4	4	4	6	6	5	7	5	-	7	5	8	4	5	7	8	9
MACS	I	II	II	II	I	I	II	II	II	I	I	II	I	I	I	I	II	II
GMFCS	II	II	II	II	I	I	II	I	II	II	II	II	I	I	I	II	I	I
									Post mCIMT									
CA	0	5	5	0	6	9	9	8	9	0	9	9	9	9	10	12	0	12
MA	0	5	5	0	6	8	8	8	7	0	8	8	8	7	8	10	0	10
MACS	0	II	II	0	I	I	II	I	II	0	I	II	I	I	I	I	0	II
GMFCS	0	II	II	0	I	I	II	I	II	0	II	II	I	I	I	I	0	I

the bandage and how to perform the mCIMT activities at home were taught to participants' parents by the specialists. However, physical, and occupational therapies were attended by the participants at the rehabilitation center once a week. Each one was a one-hour session.

In the physical therapy sessions proprioceptive neuromuscular facilitation techniques [27] were applied to each participant by the physiotherapist to reduce muscle tone and improve joint ranges. Functional exercises (transfers, crawling, going up and down stairs) were performed by the participants too.

On the other hand, the main occupational therapy activities included improving grip types (spherical, cylindrical, hooked), stimulating fine grasping (index-thumb), object displacement, grip strength, visual-motor coordination, daily day activities (zipping, buttoning, lacing), distance measurement, and graphic-writing. In addition, a task in both areas was assigned to each participant when visiting the rehabilitation center. For example, putting beans in a bottle, putting on and off a jumper without help, and removing shoelaces; these tasks were carried out at home, and tasks completion evidence (videos) were taken by the participant's parents.

E. STATISTICAL ANALYSIS

The statistical analysis of the obtained data by the NUI assessment system was done using MATLAB - R2017b. The differences in joint angles and FMA scores before and after the mCIMT intervention were verified with a Wilcoxon rank sum test equivalent to the Mann-Whitney U-test. The considered significance level was alpha = 0.05.

III. RESULTS

The obtained mean and resulted p-value of shoulder abduction, elbow flexion movement measurements and FMA for pre- and post-mCIMT are summarized in Table 2. As can be observed, no significant difference of elbow angles was achieved after the mCIMT intervention ($p < 0.05$).

TABLE 2. Measurements pre- and post- mCIMT.

Variable	Case	Mean ± SD	H_0	*p*-value
Shoulder abduction	Pre-mCIMT	84.97 ± 29.82	1	0. 0419
	Post-mCIMT	103.88 ± 35.86		
Elbow flexion	Pre-mCIMT	109.98 ± 44.70	0	0.1099
	Post-mCIMT	120.83 ± 33.93		
FMA	Pre-mCIMT	59 ± 7	1	0.0273
	Post-mCIMT	60 ± 7		

SD: standard deviation; $H_0 = 0$: No significant measurement differences were resulted between the two cases; FMA: Fugl-Meyer Assessment.

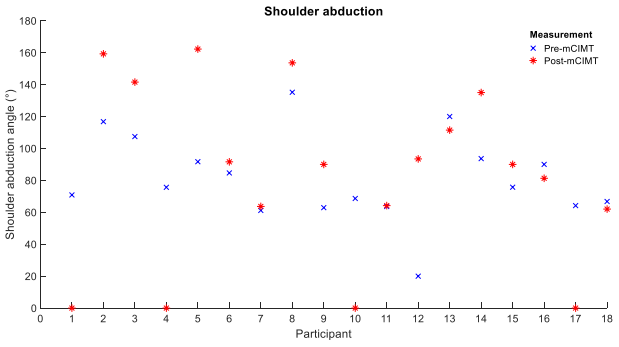

FIGURE 4. NUI measurements of shoulder abduction movement.

However, significant differences can be observed in abduction movement and upper extremity FMA motor performance at the first and last assessment (after mCIMT) ($p < 0.05$).

The shoulder abduction angles for each participant measured by the NU system, before and after the mCIMT intervention, are shown in Figure 4. As can be noted significant differences were achieved by most of the participants. A full Active Range of Motion (AROM) in the abduction movement is a difficult task to achieve for children with hemiparesis.

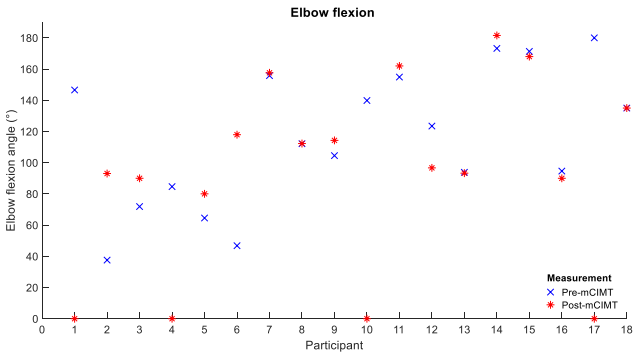

FIGURE 5. NUI measurements of elbow flexion movement.

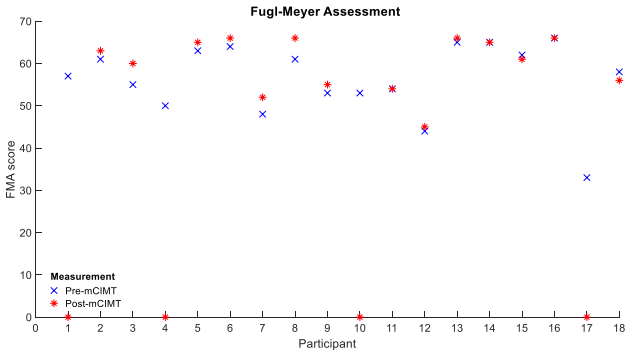

FIGURE 6. FMA scores obtained through NUI system.

After the intervention, a greater mobility was achieved by the participants ranging from 65 up to 135.

As can be seen in Figures 4-6 participants 1, 4 10 and 17 were assigned a score of 0 for flexion, abduction and FMA movements in the post mCIMT, respectively. The reason is because these participants dropped out the rehabilitation treatment.

Similarly, the elbow flexion angles for each participant measured by the NU system, before and after the mCIMT intervention, are shown in Figure 4. In this case a minimal variability is observed, so in general no significant improvement in performing this movement was achieved. The FMA scores that the participants obtained through the NU system, before and after the mCIMT intervention, are shown in Figure 5. A notable variability is depicted for this case.

IV. DISCUSSION

The mCIMT effectiveness has been supported by several reported works [6], [7], [8], [28]. In this study, the NUI measurements obtained after the mCIMT intervention has shown significant improvements in abduction movement, and motor performance FMA scores. In this way, the mCIMT effectiveness has been quantitatively verified through the NUI system applied to the described case study (Table 2, $p > 0.05$). The obtained NUI measurements were validated through a goniometer resulting a maximum absolute error of $\pm 1°$ [21].

According to the NUI measurement results (Figure 5), after the mCIMT intervention 86% of the participants showed significant motor performance improvements, 71% achieved an increase of two FMA score points, and 14% resulted in a smaller FMA score. The participants also had less mobility in forearm pronation/supination and wrist circumduction movements.

From the assessment before the mCIMT intervention it was observed that the greater gap between chronological and mental ages, the lower motor performance, which results were from limited to remarkable motor skills. The maturity of the visual-motor perception is reflected by the mental age, such condition is individual and can be affected by sociocultural factors, time, place, and current health conditions. The applied assessment to the case study participants implied new challenge tasks, which could be difficult to perform in the first assessment. The fact that the participants were already familiar with such tasks might contributed to the higher score achieved in the second assessment.

From a total of 8 participants resulting with a MACS level I after the mCIMT intervention, no change in both chronological and mental ages resulted in two participants, a one-year mismatch resulted in three participants and two-year mismatch was obtained in three participants. However, a total motor performance ability for upper limb was shown by all the participants with a MACS level. Six participants with a MACS level II were detected after the mCIMT intervention, two of them resulted with match in chronological and mental ages and two with a two-year mismatch. Similarly, a participant with a one-year age mismatch achieving a remarkable motor performance ability was found. A participant with a one-year age gap with a limited motor performance capacity was also observed. The effectiveness of the mCIMT intervention cannot be generalized since its optimal application depends on the individual participant and both cognitive and motor conditions. In general, according to the resulted FMA score 93% of the study participants resulted in a total motor performance ability (52-66), and 7% in a remarkable motor ability (47-52). However, it is worth to note that test activities were difficult to perform in 50% of the participants, mainly those requiring hand and wrist movements, performing partial movements predominantly in pronation and supination of shoulder and elbow.

A lack of coordination and speed was the reason that 14% of the participants did not achieve the maximum FMA score. The obtained minimal clinically important difference (MCID) after the mCIMT intervention was ± 7 ($p = 0.0273$) (Table 2) in the FMA score for participants with hemiparesis due to cerebral palsy. Although the resulted MCID is a small value, it represents the difference between the patient being completely functional and independent or not. This work was focused on quantitatively analyzing the mCIMT effects using the measurement system, which includes the FMA computing algorithm. Particularly, the analysis was done assessing the elbow flexion and shoulder abduction movements, as well the FMA scores.

TABLE 3. Characteristics of the nui system and manual evaluation.

Method	Instrument/ device	Assessment	Evaluation time	Accuracy (°)	MACS/ GMFCS level	Illumination (lx)	Area (m^2)	Advantages	Disadvantages
NUI System	Kinect V2	No direct patient contact (active)	6 patients per hour	±1	I-II	7-73	9	Not dependent on physiotherapist´s experience, low cost, markless.	Inaccurate measurements of ulnar and radial deviations of the upper limbs.
Manual	Goniometer	Direct (passive)	2 patients per hour	±1	I-V			Inexpensive, transportable, easy to use.	Accuracy, its correct use depends mainly on the physiotherapist's experience.

lx: lux; m: meters

Finally, the obtained results indicate that an mCIMT intervention consisting of a two-hour session five days a week along twelve weeks is an effective rehabilitation treatment for improving upper extremity motor performance in children with spastic hemiparesis. Furthermore, the described NUI measurement system is an effective and alternative measurement tool. In contrast to passive measurement techniques, the AROM analysis and the quantitatively measurement of upper limb motor performance are possible to the therapist through the NUI system. The range of motion of elbow flexion range was measured in [29], using a manual goniometer, spatiotemporal parameters were also measured through a Spasticity Assessment System (SpES). An electro goniometer for obtaining angular data is integrated in such measurement system. The used measurement technique is optimal but a direct contact with the patient is required.

On the other hand, no direct contact with the patient is employed in the described NUI measurement system, it is based on a non-invasive low-cost method.

As it is referenced in several reported studies, the Vicon motion capture systems are considered the gold standard and most frequently used measurement system for cerebral palsy patients, but its high cost is not always affordable for most patients [30].

The main characteristics of the NUI assessment system and manual evaluation are depicted in Table 3, where advantages/disadvantages are highlighted. A comparison between measurement instruments applied in a control group has been previously reported in [21].

The NUI measurement system is considered a low-cost tool because no large spaces, markers, or many cameras are required. Although the Kinect v2 sensor is coming out of the market, the NUI measurement system methodology can be easily adapted to new existing versions, for instance, the Azure Kinect sensor [31].

V. CONCLUSION

The use of the NUI system as a measurement tool to quantitatively determine a rehabilitation therapy intervention efficiency has been described in this paper. Particularly, the NUI system allowed an objective monitoring of the angular changes in shoulder abduction and elbow flexion angles for children with spastic hemiparesis after the mCIMT intervention, which consisted of two-hour rehabilitation session five days a week along twelve weeks. Additionally, the use of the NUI measurement system based on the semi-automated Kinect v2 sensor made possible to identify which upper limb movement was still motorically limited after the mCIMT intervention.

The NUI quantitatively measurement might be a helpful alternative tool to health experts for clinical assessment of upper limb movements and motor performance. The quantitative and objective measurement allows the monitoring of the rehabilitation progress or regression of a patient with hemiparesis. Nowadays it is very relevant the use of technology in the health sector, because of its accurate measurements and human error reduction due to qualitative measurements.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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