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Wearable sensors for measuring spontaneous upper limb use in children with unilateral cerebral palsy and typical development

Elena Beani[1,2†], Mattia Franchi de 'Cavalieri[2,3†], Silvia Filogna[2*], Veronica Barzacchi[2,3], Matteo Cianchetti[4,5], Martina Maselli[4,5], Giada Martini[2], Valentina Menici[2,6], Giuseppe Prencipe[7], Elisa Sicola[2], Giovanni Cioni[2] and Giuseppina Sgandurra[1,2]

Abstract

Background Unilateral Cerebral Palsy (UCP) is a clinical condition which mainly involves the movement and muscle tone of one side of the body, often impacting the general manual function. While there are some clinical assessment tools aimed to quantify the Upper Limbs (UpLs) use and the manual abilities, acquiring information regarding the motor abilities outside the clinical environment, such as the UpLs use and their asymmetry during daily life, could provide a more complete evaluation of the child and open a new clinical reasoning. For this purpose, wearable sensors are one of the newest approaches for continuously monitoring UpLs functions without being invasive. The aim of this study was to use wearable sensors to compare spontaneous/daily UpLs usage and asymmetry with the Assisting Hand Assessment (AHA) test, as well as comparing the daily UpLs usage behavior of children with UCP with respect to Typical Developing (TD) peers.

Methods Eighty children (54 with UCP and 26 TD) wore an Actigraph sensor on each wrist during the AHA test and then at least for the following week of daily life. The amount of use of each hand and the asymmetry were analyzed during both the AHA and the following week of daily life using linear regression analysis and ANOVA models.

Results Significant relationships were found between the asymmetry detected during the week and both the AHA scores and the asymmetry detected during the test. UCP and TD children week asymmetry distributions were significantly different; moreover, some differences were found when grouping them by MACS levels.

Conclusion This paper proposes a new and easy technological methodology for monitoring UpLs behavior in daily life. Through wearable sensor data analysis, we demonstrate a linear correlation between asymmetry measured during smi-structured assessments and daily life. Additionally, we provide evidence of distinct patterns of UpLs usage between typically developing children and children with UCP in daily life.

Trial registration Clinical Trials.gov (NCT03054441).

†Elena Beani and Mattia Franchi de 'Cavalieri share first authorship based on equal contribution.

*Correspondence:
Silvia Filogna
silvia.filogna@fsm.unipi.it

Full list of author information is available at the end of the article

Keywords Accelerometers, Cerebral palsy, AHA, Actigraph, Asymmetry, Daily life, Wearable sensors, Upper limb, Monitoring, UCP

Introduction

Activities of Daily Living (ADLs) are those skills required to manage everyday physical needs, such as personal care, getting dressed and eating. In these activities, the use of Upper Limbs (UpLs) is essential, as shown by the significant relationship between self-care ability and manual ability reported in literature [1, 2].

In general, most of the ADLs are bimanual, meaning that cooperation between the two hands is required: the dominant hand acts directly, whereas the non-dominant hand supports the action. This different hand role is called handedness [3] and it is generally due to differentiation of UpL motor functions during typical development [4].

UpL impairments can result in a lack of cooperation between the two hands, which compromises the goal of the action. This is what often happens in Unilateral Cerebral Palsy (UCP), (i.e., the most common form of Cerebral Palsy), where the impairment of the movement and muscle tone often affects only one side of the body. This is most common in the UpLs. UpL dysfunctions can affect reaching and grasping skills, impacting the ADLs with different levels of severity. This negatively affects the quality of life [5] and the participation in different contexts, such as at school, increasing social isolation and slower learning processes [6].

It is possible to generally describe how children with UCP use their hands in daily life activities with classification systems such as the Manual Ability Classification System (MACS), which uses a 5-point Likert scale to assess the degree of independence and success in performing everyday activites [7]. On the other hand, specific evaluations of UpL abilities are traditionally carried out within clinical settings through standardized clinical scales [8]. These scales include the Assisting Hand Assessment (AHA), the only recognized test that assesses the role of the affected hand in bimanual activities with a semi-structured playing session [9], as well as tests for assessing individual UpLs, such as the Melbourne Assessment (MUUL and its latest version, MA2), the Shriners Hospital Upper Extremity Evaluation (SHUEE), and the Quality of Upper Extremity Skills Test (QUEST).

Stating the impact on ADLs, it is pivotal to measure how this limitation could interfere in the real-life ecological environment. As the World Health Organization's International Classification of Function, Disability, and Health (WHO-ICF) states, the ability to execute tasks in a structured environment, prompted by a direct request, could be different from what a person usually does in a free-living setting; these behaviors are namely capacity and performance, respectively [10]. For this purpose, clinicians could use questionnaires addressed to caregivers, such as the ABILHAND-Kids or the Children's Hand-use Experience Questionnaire (CHEQ), which could provide information about spontaneous behaviors during daily life [8].

In addition to clinical tools and questionnaires, wearable technologies could be used to integrate quantitative and objective data into clinical assessments, as well as to monitor UpL movements in an ecological environment. Commercially available technologies, particularly wrist-worn sensorized devices (i.e. accelerometers, IMUs and smartwatches), have the tremendous power to objectively monitor UpL activitiesoutside clinical settings [11, 12], providing insightful and objective information that classifications and questionnaires alone struggle to provide; furthermore, they show high reliability and require little effort by the end users [13], constituting an optimal choice for the aforementioned purposes. These devices are also used on children older than one year, since the use of accelerometery on younger infants is highly challenging; while some authors consider this approach unreliable [14], others have obtained promising findings [15–17].

UpL behavior evaluation in both structured and unstructured situations is crucial for identifying and assessing atypical motor behaviors and tailoring rehabilitation programs. To perform this evaluation, it is critical that the chosen clinical assessment reference tool can reliably reflect typical daily life performance.

The most common clinical assessment tool already used in literature with wearable sensors is the AHA, widely used to assess the UpL clinical performance of children with CP [13, 18] and to validate the use of Actigraphs in children with UCP [18], showing evidence in objectively estimating the level of UpLs impairment while performing the AHA assessment [18].

To our knowledge, only a few works have started to investigate UpL usage during daily life in children with UCP [11], reporting the relation between the clinical and technological data. Hollis and collaborators [11] were among the first who investigated children's asymmetry thanks to long-lasting Actigraphy data: they collected 48 h of recording in both children with UCP and TD children, comparing it with the results obtained during clinical UpL tests, such as the AHA, Melbourne Assessment, and Box and Block Test. Similarly, in [19], Hoyt and collaborators compared up to 100 h of daily life UpL asymmetry with the MA2 results of TD and UCP children. However, the first group correlated the clinical data with the recording of a small period of daily life, while the second aimed to distinguish between children with and without motor deficits. Despite this, both groups agree that actigraphy may be a valuable complementary tool for measuring arm movement.

In this framework, the overall aim of this work is to evaluate UpL asymmetry as measured by wearable sensors as a valid tool for the estimation of UpL motor impairment of children with UCP outside the clinical environment in a spontaneous and ecological context as daily life. The hypothesis is that the asymmetry showed during a week of daily life could be consistent with the asymmetry reported during the clinical assessment, and, consequently, to the child's motor impairment level.

Methods

Participants

A total of eighty subjects aged between 5.4 and 19.7 years old, with a mean age of 10.7 ± 4.17 years were included in this study. Out of these, 26 subjects without clinically documented disorders were classed as TD, while the remaining 54 subjects with UCP were included if they were diagnosed with a spastic form of UCP, mild to moderate manual abilities (expressed as MACS levels 1 to 3) and no additional progressive neurological disorders, cognitive impairments or sensory deficits. The MACS level was estimated by clinicians together with caregivers. The subjects were then administered the AHA test while wearing Actigraphs on the wrists (described below). Sample characteristics are shown in Table 1.

All participants were recruited and evaluated at IRCCS Fondazione Stella Maris, (FSM, Pisa, Italy), where participants and/or their parents signed an informed consent before the trial. The Tuscany Paediatric Ethics Committee (Italy) approved the study (78/2016). This study was subsequently registered on clinicaltrials.gov (NCT03054441).

In addition, participants were asked to wear the Actigraphs at homefor the following week, and to annotate in a diary the time periods where the Actigraphs were removed to monitor the actual wearing time; from this information, we calculated the sensor wear time percentage across the week for each subject.

Table 1 Characteristics of the subjects included in the present work

Subjects	Gender (male-female)	Dominance (right-left)	Age (years) Mean ± SD	AHA Mean ± SD
TD (n = 26)	15 M 11 F	22 R 4 L	10 ± 4.3	100
UCP (n = 54)	33 M 21 F	20 R 34 L	10.9 ± 4.3	56.1 ± 15.5
MACS 1 (n = 14)	10 M 4 F	8 R 6 L	12.6 ± 4.5	70.9 ± 8.7
MACS 2 (n = 31)	16 M 15 F	18 R 13 L	10.3 ± 4.0	55.2 ± 12.0
MACS 3 (n = 9)	7 M 2 F	8 R 1 L	10.2 ± 3.4	36.1 ± 9.4

Assisting hand assessment (AHA)

The Assisting Hand Assessment (AHA) is a semi-structured video-recorded assessment of the spontaneous use of the affected hand in bimanual tasks. The test is administered in an age-related context: free play for children from 18 months to 5 years, the prisoner or alien game for children from 5 to 12 years, and different types of games for adolescents older than 13 years, such as an ad-hoc board game called "Go with the Floe", the Sandwich task, and the Present task. It requires 15 min of play with a standardized kit of toys, and the final result is scored by a certified operator based on the video recording of the session. The same AHA scoring criteria can be used across all versions and age ranges. The AHA score is built on a Rasch measurement model, which converts raw scores into a linear measure located on a unidimensional scale that ranges from 0 to 100 logit-based AHA units (where higher scores mean better integration of the hands). This score is commonly used in statistical analyses [9, 20, 21].

Manual ability classification system (MACS)

The Manual Ability Classification System (MACS) describes how children with CP from 4 to 18 years old usually use their hands to perform everyday activities (i.e., eating or getting dressed), and whether they may either require assistance from others or require the task to be adapted. The clinician and caregivers assign the MACS level which best fits the child's typical performance by referring to the overall competence in handling, regardless of the individual ability of either hand.

It has five levels, from low to high impairment, but children with UCP are commonly found on levels I to III. In brief, a child at level I handles objects easily and successfully; at level II the child handles most objects less precisely and more slowly, and alternative ways of handling objects may be used; at level III a child handles objects with difficulty and commonly needs help to prepare and/or modify daily life activities [7].

Upper limb movement data acquisition set up

Each participant wore a pair of activity monitors (wGT3X-BT Monitor, ActiGraph, Florida, FL, model 7164; 4.6 cm × 3.3 cm × 1.5 cm, 19 g, Firmware v1.8.0), one on each wrist both during the AHA clinical evaluation session and during an entire week, with the guidelines of wearing them as much as possible. The wearing on the wrist was possible thanks to the Velcro® hypoallergenic wristbands provided together by Actigraph that were easily adaptable to different wrist sizes. The single activity monitor consists of a tri-axis accelerometer with a dynamic range of +/- 8 g, able to accurately detect the accelerations associated with the movement of the upper arm on which it is placed. The sampling rate of the acceleration signals was set to 80 Hz, and the data were stored locally on non-volatile flash memory, in gravitational units (i.e., 1 g is equal to the Earth standard gravitational unit). At the end of the acquisition, we had data recorded both during the AHA test and during a real-life week. Data collection for the week started at midnight of the day following initialization until the end of the 7th day, resulting in 6 full days of data acquisition, including the night slots.

Based on raw acceleration data, a proprietary software (ActiLife® software, v6.13.4) computes the Activity Count (AC) index, which is an indicator of the amount of movement of the limb the unit is paired to along each axis of acquisition (i.e., x, y, and z). The AC data can be generated with a specific time-frequency (the epoch): the software first calculates the AC at 1 Hz, resulting in a 1-second epoch; then, based on the 1 Hz data, longer epochs (i.e. lower frequencies) were obtained by adding the 1-second epoch's ACs across the desired time span. This is possible due to the AC's time-additivity property. The software allows the user to obtain ACs in epochs from one second to four minutes. For the week data, the epoch was set to 4 min to reduce the computational burden of the analysis, while the AHA data had an epoch of 1 s since the trial lasted no more than 30 min. ACs were then stored in comma-separated value format (.csv) files along with some metadata, including the starting date-time of the acquisition, the defined epoch period, and the device serial number. Finally, the data were imported and analyzed with MATLAB software (version 9.9, The MathWorks Inc., Natick, MA, USA).

For each participant, the vector magnitude of the AC was computed for both the dominant and non-dominant hand (which, for subjects with UCP, was the affected hand) during each epoch period *i*, as:

$$AC\left(i\right) = \sqrt{AC\left(i\right)_x^2 + AC\left(i\right)_y^2 + AC\left(i\right)_z^2} \quad (1)$$

where $AC\left(i\right)_x$, $AC\left(i\right)_y$, and $AC\left(i\right)_z$ were the AC calculated along the relative axis of acquisition (i.e., x, y, and z, respectively). The AC Starting from the ACs recorded by the ActiGraph monitors, the Asymmetry Index (AI) was used in [18] as an indicator of the different usage of the UpLs by a single subject across a certain time period. The AI is defined by the following formula:

$$AI = \frac{\sum_{i=1}^{N} AC\left(i\right)_D - \sum_{i=1}^{N} AC\left(i\right)_{ND}}{\sum_{i=1}^{N} AC\left(i\right)_D + \sum_{i=1}^{N} AC\left(i\right)_{ND}} * 100 \quad (2)$$

where $AC\left(i\right)_D$ and $AC\left(i\right)_{ND}$ are, respectively, the AC vector magnitude of the dominant and non-dominant hand for each epoch (1) i, and N is the total number of epochs constituting the period of interest; when the formula denominator was equal to zero (i.e., no movement detected from either one of the arms) the AI was set to zero as well. The AI index ranges from – 100 to 100 and it can be seen as a percentage of asymmetry of the subject's UpL use: if the AI is 0%, there is no asymmetry; if the AI is 100%, only one arm is being used, resulting in full asymmetry (-100% and + 100% for the non-dominant and dominant arm, respectively) For each participant, we obtained the AI_{AHA} by calculating the asymmetry during the clinical session, and the AI_{WEEK} by computing the asymmetry during the week.

Finally, we aimed to evaluate the average use of the single UpL during daily life. To do this, we computed the means of the activity counts acquired from both the dominant and non-dominant UpL (i.e., $AC\left(i\right)_D$ and $AC\left(i\right)_{ND}$) across the week 4-minutes epochs for each subject; the resulting variables $\bar{AC}_{D,week}$ and $\bar{AC}_{ND,week}$represented the mean use of the dominant ($\bar{AC}_{D,week}$) and non-dominant $\bar{AC}_{ND,week}$) UpL during the week.

Statistical analysis

In order to study the relation between the clinical assessment and the UpL asymmetry measured using the Actigraphs during the clinical session and validate the use of the asymmetry for estimating the level of impairment of the subjects, we first applied a linear correlation and then a linear regression to compare the AI_{AHA} distribution of the whole sample (i.e., subjects with TD and with UCP) with the AHA clinical scores as the dependent variable. After that, we investigated the relation between the clinical assessment and the UpL asymmetry during the week to demonstrate that this parameter can be a valid tool for studying the motor behaviour of children in an ecological and unstructured environment; to achieve this, we applied a linear correlation and a linear regression model between the AI_{WEEK} distribution of the whole sample and the AHA clinical scores as the dependent variable.

After the validation of the asymmetry indexes thanks to the comparison with the AHA scale, we wanted to use them to analyze the relation between the UpL behaviour during the clinical assessment and during daily life; to achieve this, we used a linear regression model between AI_{AHA} as the dependent variable and AI_{WEEK}. We performed this analysis by first considering the entire subject sample and then examining subjects with TD and subjects with UCP separately in order to better understand the results by taking the underlying population

Table 2 Linear correlation results between AHA clinical score, AI_{AHA} and AI_{WEEK}. Symbol * shows significant difference

AHA	*R*	CI 95%	*P*-value
AI_{AHA}	-0.92	[-0.95; -0.88]	< 0.001*
AI_{WEEK}	-0.89	[-0.93; -0.83]	< 0.001*

Table 3 Linear regression model results using AHA clinical score as the dependent variable. Symbol * shows significant difference

	Estimate	Adjusted *R*-squared	*P*-adjusted
AI_{AHA}	-0.91	0.85	< 0.001*
AI_{WEEK}	-1.34	0.79	< 0.001*

differences into account. Then, we wanted to understand if the asymmetry showed during the clinical assessment is reflected in single UpL use during the week; we therefore used linear regression to compare AI_{AHA} against $\bar{AC}_{D,week}$, and $\bar{AC}_{ND,week}$; for this analysis, for this analysis, we compared TD subjects and UCP subjects separately to better differentiate their behavior.

Finally, we analyzed the various populations during the week to investigate if there are clear differences in the combined UpL use during daily life between the subject groups. To achieve this, we compared AI_{WEEK} distributions of TD subjects and subjects with UCP, first as a whole and then grouped by MACS levels using ANOVA.

All the regressions were assessed by computing the Adjusted R-squared index for the models' accuracy. Correlation performances were evaluated using the R value together with the 95% CI and the p-value with a statistical significance threshold of 0.05; for all the other analyses, adjusted p-valueswere determined for statistical significance with a threshold of 0.05. All analyses were performed using the R language for statistical computing, version 4.3.1.

Results

During the week, all subjects wore Actigraphs for a mean percentage of 80,95%, including nighttime periods.

The outcomes of the correlations and the linear models between the AHA clinical assessment scores and the UpL asymmetries measured using the Actigraphs are reported in Tables 2 and 3. The results demonstrate strong and negative statistically significant relations between the AHA clinical scores and the UpL asymmetries, either during the clinical session in a structured environment (AI_{AHA}) and in a highly ecological environment such as daily life (AI_{WEEK}). The negative estimates of the correlations between the clinical scores and the asymmetries measured during the clinical sessions are expected: in fact, lower UpL asymmetries are related to higher performances during the assessment, resulting in higher AHA scores.

Focusing on technological data (i.e. asymmetries), we found a relation between structured and ecological settings; in Fig. 1 and Table 4 we reported the linear regression results between the AI_{AHA} and AI_{WEEK} distributions by considering all subjects, TD subjects and subjects with UCP. We also highlighted that the mean use of the non-dominant UpL during the week ($\bar{AC}_{ND,week}$) reflects the asymmetry showed in the clinical environment if we consider all subjects and subjects with UCP; the linear regression models outcomes are reported in Table 4, while Fig. 2 visualizes the TD and UCP population hands in relation to the asymmetry during the standardized evaluation session.

Finally, Table 5 shows the AI_{WEEK} distributions features, while Table 6 reports the AI_{WEEK} distribution comparisons, first between TD subjects and subjects with UCP, highlighting that the TD population manifests lower asymmetries with respect to children with UCP during daily life, and then of subjects with UCP grouped by MACS level (b), reporting a significant difference between the MACS 1 and MACS 3 groups in the UpL asymmetries during daily life. The comparison of AI_{WEEK} among different groups is illustrated in Fig. 3 by using boxplot graphs.

Discussion

This work focuses on the monitoring of UpL usage and provides useful information on the motor capacities of TD children and children with UCP not only in the clinical environment, but also during daily life, opening an interesting perspective in the monitoring of spontaneous UpL use and asymmetry by means of actigraphic data. To our knowledge, it represents one of the first applications on TD and UCP subjects in the developmental age, where clinical and actigraphic data are studied in both a structured environment and in highly ecological environment such as daily life.

One of the main results is the high wear time percentage during daily life by the whole sample, despite the wide age range, high variability in the functional level of participants and various daily routines. Therefore, we confirmed that Actigraphs were acceptable for subjects in the developmental age and their families and that these results open the possibility to exploit the use of this approach as a novel method for acquiring UpL data during daily life.

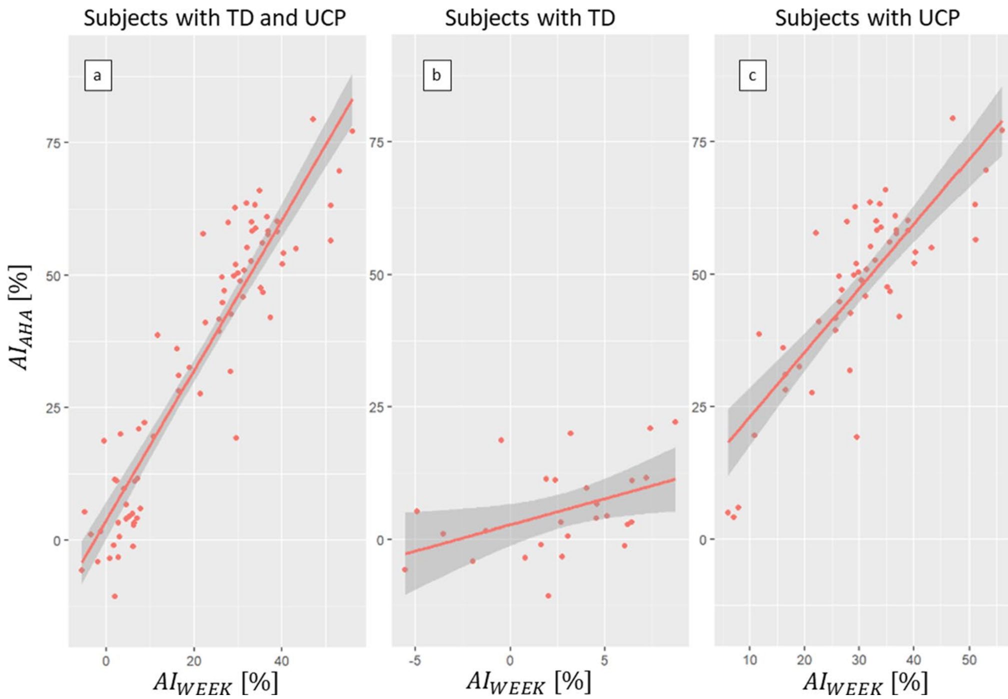

Fig. 1 Daily life and clinical UpLs asymmetry relations scatter plots and linear regression results (solid line, grey areas for standard deviation) of the AI_{WEEK} versus AI_{AHA} of the entire sample (**a**), of subjects with TD (**b**), and of subjects with UCP (**c**)

Table 4 Linear regression results using AI_{AHA} score as the dependent variable. Symbol * shows significant difference

Population	Variable	Estimate	Adjusted *R*-squared	*P*-adjusted
Total	AI_{WEEK}	1.42	0.86	< 0.001*
	$\bar{AC}_{D,week}$	-0.0009	0.01	0.15
	$\bar{AC}_{ND,week}$	-0.0040	0.45	< 0.001*
TD	AI_{WEEK}	0.98	0.16	0.026*
	$\bar{AC}_{D,week}$	0.0003	-0.04	0.416
	$\bar{AC}_{ND,week}$	0.0001	-0.04	0.739
UCP	AI_{WEEK}	1.21	0.67	< 0.001*
	$\bar{AC}_{D,week}$	-0.0006	0.01	0.23
	$\bar{AC}_{ND,week}$	-0.0032	0.30	< 0.001*

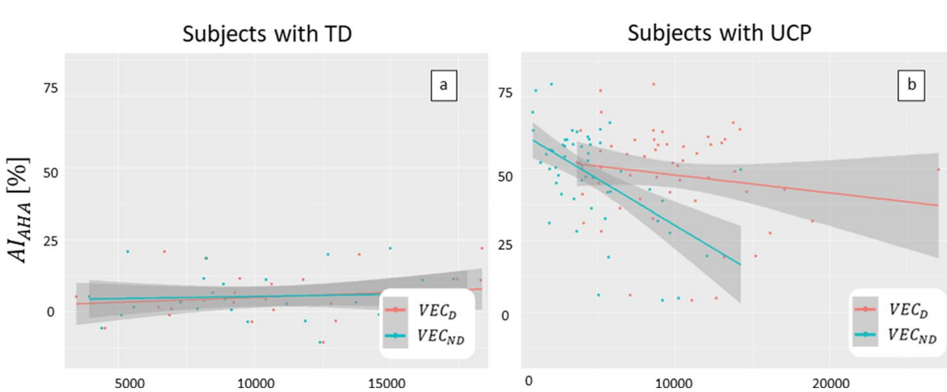

Fig. 2 UpLs use during daily life Scatter plots and linear regression results (grey areas for standard deviation) of VEC_D (red colour) and VEC_{ND} (green colour) variables versus AI_{AHA} of subjects with TD (**a**), and those with UCP (**b**)

Table 5 Subject's AI_{WEEK} distributions features

Population	25th percentile	Mean	Median	75th percentile
TD	1.01	2.67	2.90	5.83
UCP	25.86	30.39	30.81	36.40
MACS 1	16.09	24.27	22.60	35.57
MACS 2	28.46	32.00	31.97	36.85
MACS3	25.70	35.05	33.83	36.88

Table 6 Statistical comparison of AI_{WEEK} distributions between different subject populations. Symbol * shows significant difference

	Means difference	*p*-adjusted
TD vs. UCP	-27.71	< 0.001*
MACS 1 vs. MACS 2	-7.14	0.076
MACS 1 vs. MACS 3	-10.41	0.043*
MACS 2 vs. MACS 3	-3.27	0.776

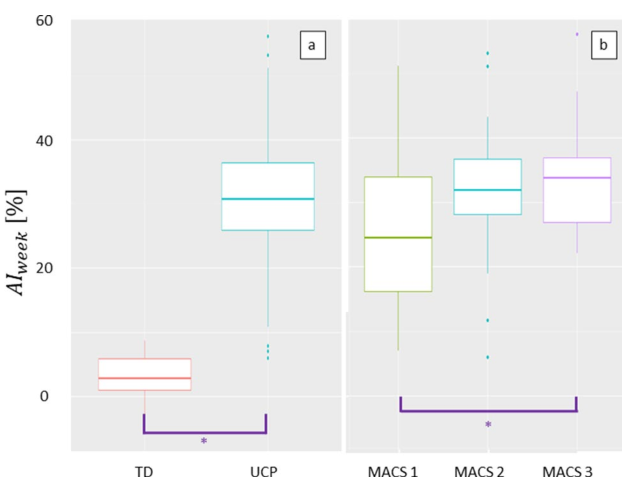

Fig. 3 Daily life asymmetry distributions AI_{WEEK} distribution boxplots for subjects with TD and those with UCP (**a**), and AI_{WEEK} distribution boxplots of subjects with UCP divided by MACS levels (**b**). Significant distributions differences are reported with the * symbol

Even though the sample presented a high heterogeneity, related to factors such as the functional level of participants or the different daily routines, the linear regression outcomes presented in Table 2 confirm the relation between clinical and technological data during the clinical assessment with the AHA found in [18]. This important result supports the validity of the AHA in assessing children's typical performance; in fact, in this test, the scoring is based on the child's spontaneous behaviour while handling toys which typically requires bimanual hand use. Although the AHA primarily focuses on the functioning of both the UpLs, particularly the hand, and the Actigraphs record the magnitude of movement of the two UpLs and their relationship, both methods are consistent in measuring the subject's UpL usage. It needs to be underlined that some authors [22] question the use of Actigraphy for detecting arm functions effectively during daily life. However, they analyzed data of a relatively narrow time range focusing on single arm use, while we provided evidence that the asymmetry (and not the single arm usage) correlates significantly with the clinically validated outcomes. In addition, the negative relation between the AI_{WEEK} and both the AHA score and the AI_{AHA} confirmed our past works [18], sweeping away potential doubts on the possibility of comparing the assessment and the daily life recording.

Clinical and actigraphic data are more strongly correlated during periods of high activity, as reported in Table 3. This is in line with current literature [11], though we minimized temporal bias by collecting data within a smaller time frame.

After a first analysis where we considered the whole sample, we went deeper into the analysis by separating the two groups and we found that there are some interesting differences in the behaviour between subjects with TD and those with UCP. The choice to divide the analysis between the two groups has a rationale both from a clinical and a technological point of view. In fact, in addition to the aforementioned explanations regarding the functioning of subjects with TD and with UCP, there were high differences in the arm asymmetry data distribution between these two groups in terms of both ranges mean extension; this particular factor could have caused the discrepancy in results in the analyses. This finding was also supported by Hollis [11], which found that the control participants' asymmetries scores were widely distributed for participants with stroke but not for typically developing participants, all exhibiting equivalent symmetrical behaviour. These factors indicate that building a reliable model using a combination of TD and UCP data may be challenging due to significant differences in upper limb behavior between the two groups.

Indeed, as shown in Fig. 3 and in Table 6, subjects with TD reported to be significantly more globally symmetric during the week in respect to subjects with UCP, displaying an asymmetry ranging between 1.01 and 5.83%, while subjects with UCP showed an asymmetry between 25.86% and 36.40% (Table 5). Again, we confirmed the clinical literature [23], which states that the typical arm and hand mobility is characterized by the ability to adapt to environmental constraints thanks to a wide repertoire of different possibilities,. while in UCP several aspects (such as the type of lesion and the cognitive level [24]) impact not only the motor skills, but also the strategies for integrating both hands to successfully complete daily life tasks.

Another important result is that the asymmetry detected during the AHA of the whole sample is mainly attributable to the non-dominant UpL use of subjects with UCP, regardless of the dominant UpL usage, as reported in Table 3. This could initially sound unexpected, since it seems in contrast with the existing literature, which reports that subjects with UCP usually also use their dominant hand to foster the initiative and use of the non-dominant hand [25]; however, this strategy could be related directly to the hand only and not to the whole UpL. In fact, what changes during the development of subjects with TD are the manual dexterity and the grip strength and not the arm function or the overall movement of the UpL (as in [26]). Therefore, our results fit within this concept by measuring the whole UpL movement activity, which is not often detected by the clinical outcome measures.

The choice to divide the analysis between the two groups has a rationale both from a clinical and a technological point of view. In fact, in addition to the aforementioned explanations regarding the functioning of subjects with TD and with UCP, there were high differences in the arm asymmetry data distribution between these two groups in terms of both ranges mean extension; this particular factor could have caused the discrepancy in results in the analyses. This finding was also supported by Hollis [11], which found that the control participants' asymmetries scores were widely distributed for participants with stroke but not for typically developing participants, all exhibiting equivalent symmetrical behaviour. Therefore, these results highlighted that it is not advisable to build a trustworthy model implementing UpLs daily life data coming from both TD and UCP. Finally, we carried out the analysis of the subjects with UCP by grouping them by MACS levels, which could group subjects with more similar UpL skills. The MACS describes the spontaneous use of the affected hand and the ability in achieving daily life tasks independently; Thanks to it, it is possible to study the real whole UpL usage by matching and comparing this information with a long recording of the spontaneous behaviour.

The distribution boxplots results reported in Fig. 3 and in Table 6 highlight differences between subjects with TD and with UCP and within the second group in MACS levels I Vs III, but not in I Vs II, and II Vs III. The diverse values between level I and III is to be expected; in fact, as stated in the MACS level descriptions, they have a very different level of independence. On the other hand, the insignificance in the differences between subjects in Level I and II and II and III could be related to the use of surfaces and other strategies which actually involve both hands, but with external adaptations, which cannot be detected if analysing only the amount of use of both arms and hands [7].

The insignificant difference between level II and III asymmetries reported in Table 6 can be explained by the description of MACS levels II and III, where the only appreciable difference is the need of assistance and adjustments to make the environment manageable. If we hypothesize that the subjects at level III receive the required help from their caregivers, we can assume that the number of UpL movements should be similar to that of subjects at level II, which could perform the same activities more independently.

Beside these reported new findings about the spontaneous use of UpLs in developmental age, some limitations need to be underlined: first, we analyzed our data considering the day as a whole. Perhaps, a calculation relative to the daily hour slot could highlight some interesting trends depending on the time and the related activities (such as school time, rest time, sports time, and so on). In this sense, labelling data regarding these activities could be helpful in carrying out a detailed study of UpL use, highlighting the factors which can affect their symmetry. Furthermore, we need to further analyze the relationship between the asymmetry reported during the AHA and during the week, to better understand whether the subjects are more or less symmetrical during daily life than in the assessment setting. Moreover, the functional differences in bimanual function could be different among groups, not only based on classification systems such as MACS, but also on the type of brain lesion, as suggested by [27], who reported that bimanual function is different between subjects who had perinatal arterial ischaemic stroke or periventricular haemorrhagic infarction, or on the side of the injury. Nevertheless, with the awareness of the aforementioned limits, our findings suggest that actigraphic recordings could represent an additional objective outcome measure for longitudinal development, intervention-induced changes, and everyday life behaviour, with the advantage of recording spontaneous UpL use. Moreover, actigraphy allows for the measurement of spontaneous upper limb use without the influence of repeated testing, which can lead to learning effects and altered behavior.

Conclusions

This paper further emphasizes the role of actigraphy in providing reliable data which are in line with clinical standardized tools and opens an interesting perspective on its use in unstructured contexts, such as daily life. Our results proved that a significant relation between the UpL use between clinical and daily life environments does exist, suggesting that wearable sensors can constitute a valid tool for helping the evaluation of UpL impairment outside the clinical environment; moreover, asymmetry distributions showed significant differences between TD subjects and subjects with UCP, as well as between subjects with different MACS level in the daily UpL behaviour.

Future works could aim at better evaluating day-to-day reliability and the difference between the week and week-end days; moreover, it could be interesting to identify the minimum required wearing time and number of days recorded that represent the weekly UpL use to standardize the current methodology, and to reduce both the single child data size and the computational burden of the analysis, while increasing the number of subjects to be monitored. Furthermore, the application of Machine Learning and Deep Learning algorithms could add a great value and new perspectives regarding these findings. The possibility of having these extremely detailed data could enrich the current knowledge of Cerebral Palsy, by a further development of the methodology with the aim of giving evidence about the heterogeneity of the clinical pictures of the UCP. In this direction, a detailed analysis of asymmetry by means of Actigraphs during everyday life could allow researchers to more deeply study the domains of functioning, identifying the factors which could define the responsiveness to a treatment, representing an innovative and interesting tool to help clinicians in the personalization of the intervention.

Abbreviations

CP	Cerebral Palsy
UCP	Unilateral Cerebral Palsy
UpL	Upper Limb
AHA	Assisting Hand Assessment
TD	Typical Developing.
MACS	Manual Activity Classification System
ADL	Activities of Daily Living
MUUL	Melbourne Assessment of Unilateral Upper Limb Function
MA2	Melbourne Assessment 2
SHUEE	Shriners Hospital Upper Extremity Evaluation
QUEST	Quality of Upper Extremity Skills Test
CHEQ	Children's Hand-use Experience Questionnaire
WHO-ICF	World Health Organization's International Classification of Function, Disability, and Health.
AC	Activity Count
AI	Asymmetry Index
AI_{AHA}	Asymmetry Index during the clinical session
AI_{WEEK}	Asymmetry Index during the week
VEC_D	Mean use of dominant UpL during the week
VEC_{ND}	Mean use of non-dominant UpL during the week

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Author contributions
G.S. and G.C. designed the study; E.B., S.F., G.P. and G.S. developed the methodology of the study; E.B., M.FdC. were responsible for the investigation of the study and for preparing the first draft of the manuscript; E.B., M.FdC., V.B., G.M., V.M., E.S. were responsible for the data acquisition; M.FdC., M.M., S.F., M.C. were responsible for the data curation and the statistical analysis; E.B., V.B., G.M., V.M., E.S. were responsible for the clinical assessment scoring; G.S. and G.C. were project administrator. All the authors have reviewed and agreed to the current version of the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
All families filled in a written consent to participate in the study. Ethics approval was obtained from the Tuscany Paediatric Ethics Committee, Italy (78/2016).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Clinical and Experimental Medicine, University of Pisa, Pisa, Italy
[2]Department of Developmental Neuroscience, IRCCS Fondazione Stella Maris, Calambrone, Pisa, Italy
[3]Tuscan Ph.D. Programme of Neuroscience, University of Florence, Florence, Italy
[4]The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy
[5]Department of Excellence in Robotics & AI, Scuola Superiore Sant'Anna, Pisa, Italy
[6]Programme in Clinical and Translational Sciences, University of Pisa, Pisa, Italy
[7]Department of Computer Science, University of Pisa, Pisa, Italy

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