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The reliability of upper limb kinematics in children with hemiplegic cerebral palsy

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ABSTRACT

This study describes the reliability of a protocol for upper limb three-dimensional movement analysis (UL-3DMA) in children with hemiplegic cerebral palsy (HCP). The UL-3DMA is based on the ISB-recommendations, and contains a set of functional and clinically relevant tasks. Tasks were selected to reflect the characteristic movement deficits seen in children with HCP. The protocol consists of three reach tasks (forwards, upwards, sideways); two reach-to-grasp tasks (with objects requiring different hand orientations); and three gross motor tasks. Within and between session reliability was tested in a group of 12 children with HCP, aged 6–15 years. Reliability of movement duration/speed and joint angles at endpoint was assessed with the intraclass correlation coefficient; similarity of the waveforms with the coefficient of multiple correlation. Measurement errors were calculated for all parameters.

Results indicated good within and between session reliability for movement duration/speed. Trunk, scapula, shoulder, elbow and wrist angles at endpoint generally showed moderately high to very high reliability. High levels of reliability were also found for scapula, shoulder and elbow waveforms and lower levels for the wrist and trunk. Within and between session measurement errors were below 5° and 7°, respectively, for most kinematic parameters. Joint angles in the transverse plane, as well as wrist flexion generally showed higher between session errors (7–10°).

This study indicates that the proposed protocol is a reliable tool to quantify upper limb movements in children with HCP, providing a sound base for its clinical application. Further research is needed to establish the discriminative ability of the UL-3DMA.

1. Introduction

Children with hemiplegic cerebral palsy (HCP) experience various upper limb motor and sensory impairments that contribute to the difficulties they encounter during functional activities, such as reaching, grasping, releasing and manipulating objects [1]. Improving these children's function and independence in daily life requires adequate treatment planning. However, the choice and planning of interventions necessitates a better understanding of the pathological upper limb movements. Although several reliable and valid clinical tools are currently available to evaluate upper limb movement quality during unimanual and/or bimanual tasks (Melbourne Assessment [2], QUEST [3], SHUEE [4]), some have been criticized for not being sensitive enough to detect clinically meaningful changes after intervention [5]. The main disadvantage lies within the sensitivity of the observation during task execution, as well as in scoring global movement quality using ordinal ratings. The information obtained from these existing evaluation tools could be enhanced by adding objective data from upper limb three-dimensional movement analysis (UL-3DMA).

For the lower limbs, 3D-gait analysis has proven to be a reliable tool usable for clinical decision-making and treatment evaluation in children with CP [6]. Accordingly, it is expected that UL-3DMA may also aid in treatment planning and evaluating treatment efficacy for children with HCP. Nonetheless, the need for standardization of the protocol for UL-3DMA has been emphasized by several authors [7–9]. Such a protocol entails not only the construction of a proper biomechanical model, but also the careful selection of a set of relevant tasks [9].

We therefore developed a clinically feasible 3D-measurement procedure for the objective evaluation of upper limb movements during several functional tasks [10]. Tasks were selected to reflect the pathological movement characteristics seen in children with

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HCP. Upper limb kinematics were calculated following the recommendations of the International Society of Biomechanics (ISB) [7]. This model includes five segments and 13DoF, which is the preferred approach in clinical applications to cover all possible compensatory strategies [11]. This UL-3DMA has been proven reliable and applicable in typically developing children (TDC) [10].

Clinical implementation of the measurement procedure additionally requires the establishment of its reliability in patient groups. Schneiberg et al. [12] previously reported between session reliability of endpoint spatial and kinematic parameters during reach-to-grasp objects at different distances. They reported overall moderate to excellent reliability for elbow and shoulder flexion, with measurement errors ranging from 5° to 10°. However, joint angles were computed based on a simplified kinematic model, using vectors joining skin-markers placed on the wrist, elbow, shoulder, and pelvis. Mackey et al. [13] and Reid et al. [14] assessed within and between session reliability of upper limb angular waveforms in children with HCP. Mackey et al. limited the analysis to shoulder and elbow kinematics during gross motor tasks, without applying the ISB-recommendations [13]. Reid et al. analyzed the reliability of trunk, shoulder, elbow and wrist kinematics during reaching and a gross motor task, using a variation of the ISB-recommendations [14]. None of the above mentioned studies established the reliability of scapular kinematics. Given the role of the scapula in the normal movement of the humerus, especially in children [15], it cannot be disregarded when evaluating upper limb motor performance. Additionally, measurement errors of upper limb kinematics in children with HCP have only been reported to a limited extent. Knowledge on the magnitude of the measurement error is necessary in order to distinguish clinically meaningful differences from normal variation in task execution.

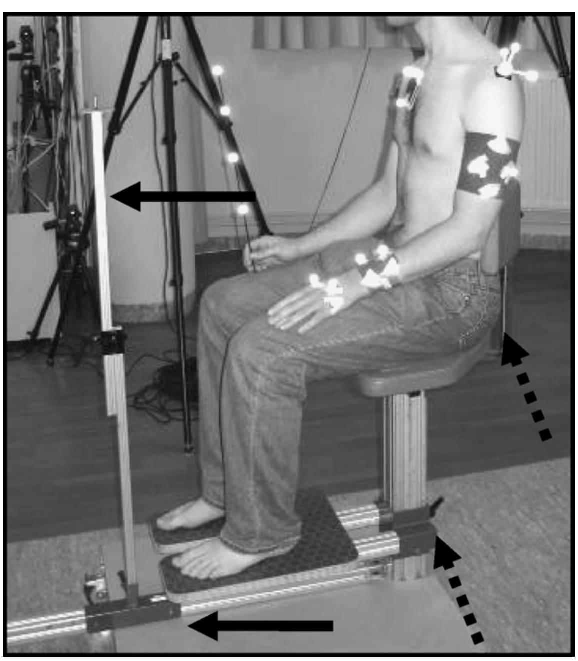

Fig. 1. (1) Marker placement: Every segment is completely defined in space by a cluster of ≥ three non-collinear markers, with a total of 17 markers. Marker clusters were used to calculate the orientation of the segmental *technical coordinate systems* (TCS) by means of singular value decompositions [18]. Anatomical landmarks (ALs) were palpated and digitized during static trials, using a pointer with four linear markers. The ALs were defined within their respective segmental TCS [19], and subsequently used to construct the segmental *anatomical coordinate systems* (ACS). Elbow and wrist joint centers were calculated based on the concurrent ALs; the shoulder rotation center was estimated based on a linear regression equation [20]. (2) Every child was seated in the custom-made chair with adjustable foot and back support (dotted arrows) and reaching distance and height (full arrows).

Therefore, the aim of this study was to determine within and between session reliability and measurement errors of the developed protocol for UL-3DMA in children with HCP.

2. Methods

2.1. Participants

Children were recruited from the database of the clinical motion analysis laboratory (University Hospital Pellenberg, Belgium), and were included if they met following criteria: (1) diagnosis of HCP; (2) aged 5–15 years; (3) minimum ability to hold an object and stabilize it for use by the other hand; and (4) sufficient cooperation to comprehend and complete the test procedure. Children were excluded in case of upper limb surgery or BTX-injections within 6 months prior to testing. Ethical approval was granted by the Ethics Committee of the University Hospital Leuven (Belgium). Written informed consent was signed by all children's parents.

Twelve children with HCP (six girls, six boys) participated in the study. They had a mean age of 10.2 years (±3.2 years), range 6–15 years. Eight children had a right and four had a left hemiplegia. Children were sampled across the first two levels of the Manual Ability Classification Scale (MACS) [16] (level I in four children, level II in eight children) and House scores [17] ranged from 3 to 8 (median 5). Children with House score 3 ($n = 2$) were not able to perform the reach-to-grasp tasks, nor the gross motor tasks.

2.2. Kinematic model

The kinematic model included five segments: trunk, scapula, humerus, forearm, and hand. Four upper limb joints were considered: scapula (scapulathoracic), shoulder (humerothoracic), elbow, wrist; as well as trunk kinematics. Anatomical coordinate systems (ACS) and joint rotation sequences were defined consistent with the ISB-guidelines [7,11].

2.3. Test procedure

Every child was evaluated on two occasions, with a mean interval of 5 days (±1.7 days), by the same assessor. Seventeen markers, clustered on small tripods and cuffs, were placed over the child's arm and trunk. Children were seated in a custom-made chair with individually adjustable foot and back support and reaching distance and height (Fig. 1). The reference position was 90° hip and knee flexion, the low back supported and hands placed on the ipsilateral knee. Reaching distance and height were normalized for arm length (distance between acromion and third metacarpophalangeal joint with the arm passively extended) and shoulder height in sitting position, respectively. The child's sitting position, reaching distance and height were carefully noted and reapplied the second session. While seated in the chair, static trials were collected to record the reference position and to digitize the anatomical landmarks relative to their respective marker cluster [19], using a pointer with four linear markers [11]. Palpation was done following an atlas including precise definitions of palpable landmarks [21].

After the static trials, children were instructed to complete the movement protocol (see Supplementary Material). The protocol contained three reach tasks: forwards (*RF*), upwards (*RU*), sideways (*RS*); two reach-to-grasp tasks: requiring forearm pronation, i.e. grasp a ball (*RGS*), or forearm supination, i.e. grasp a vertically oriented cylinder (*RGV*); and three gross motor tasks representing common daily activities, e.g. eating, grooming, dressing: hand to mouth (*HTM*), hand to head (*HTH*) and hand to contralateral shoulder (*HTS*). Reach forwards, sideways and the two reach-to-grasp tasks were executed at shoulder-height; upward reaching at eye-height. All tasks were performed at self-selected speed with the hemiplegic arm.

The start and end position of every task was defined as the hand on the ipsilateral knee, marked with rough tape. Before each trial, children were instructed to sit upright, then the task was demonstrated and they were given a practice trial. Each task was repeated four times within one single trial. Three successful trials were collected for every task, yielding 12 movement cycles per task.

3D-marker tracking was done with 12 infrared Vicon-cameras sampling at 100 Hz (Vicon Motion Analysis system, Oxford Metrics, UK), and filtered using spline-interpolation [22].

2.4. Data analysis

Movement cycles were visually identified with the stop-frame feature and frame-by-frame inspection of the moving markers. One movement cycle was defined from 'hand on ipsilateral knee' to the 'point of task achievement' (PTA), i.e. the instant when the ROM needed for successful task execution was achieved [23]. The second and third cycle of every trial were retained for data processing, as these were not influenced by potential start/stop strategies of the child, which left a total of six movement cycles per task.

Further data processing was done with Matlab®, based on BodyMech (http://www.bodymech.nl) and additional custom-written routines to calculate upper limb kinematics [11]. Movement cycles were time-normalized (0–100%) and each

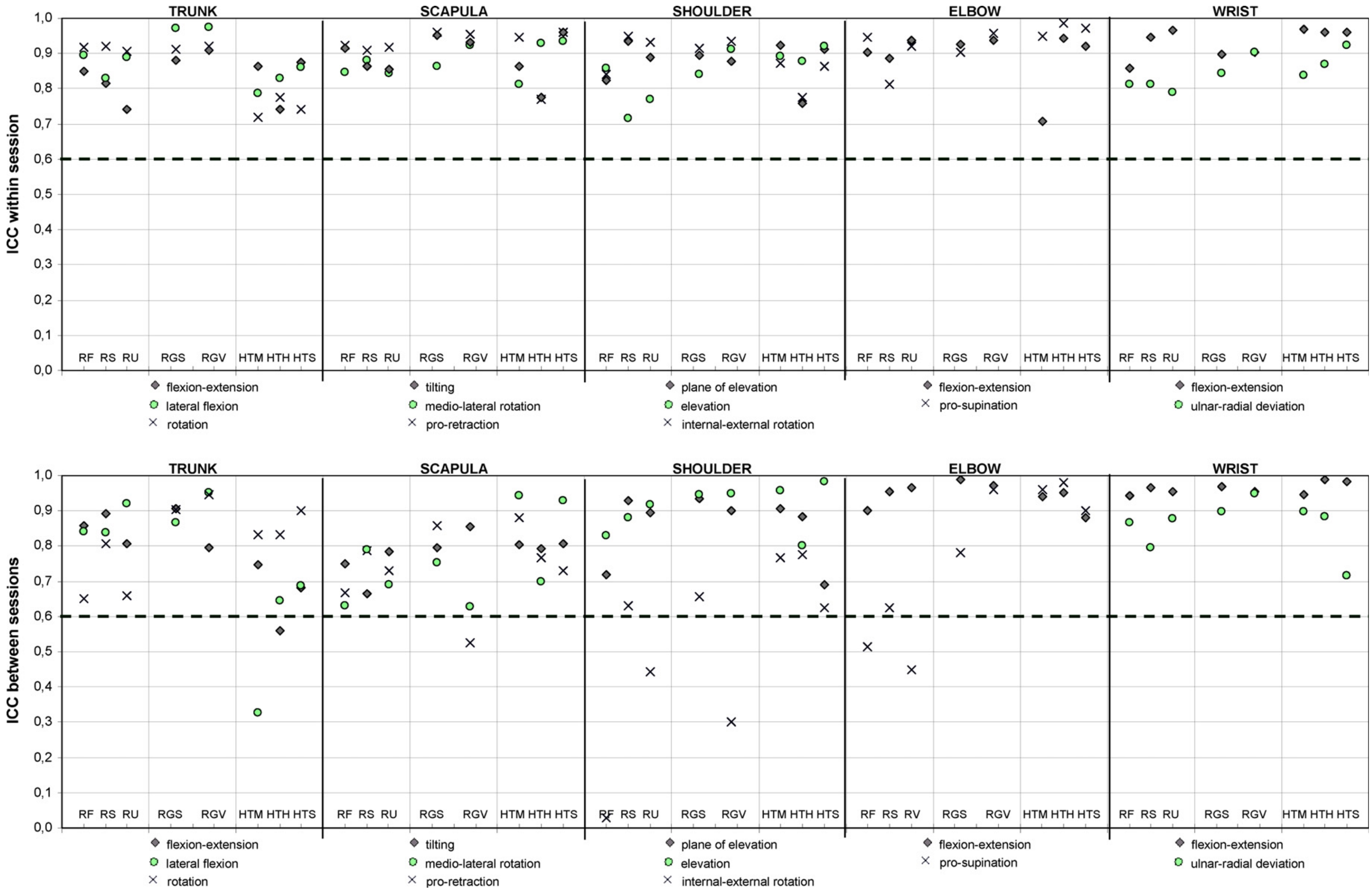

Fig. 2. Reliability of joint angles at PTA: within and between ICC per joint, for each upper limb task. RF: reach forwards; RS: reach sideways; RU: reach upwards; RGS: reach grasp spherically; RGV: reach grasp vertically; HTM: hand to mouth; HTH: hand to head; and HTS: hand to shoulder.

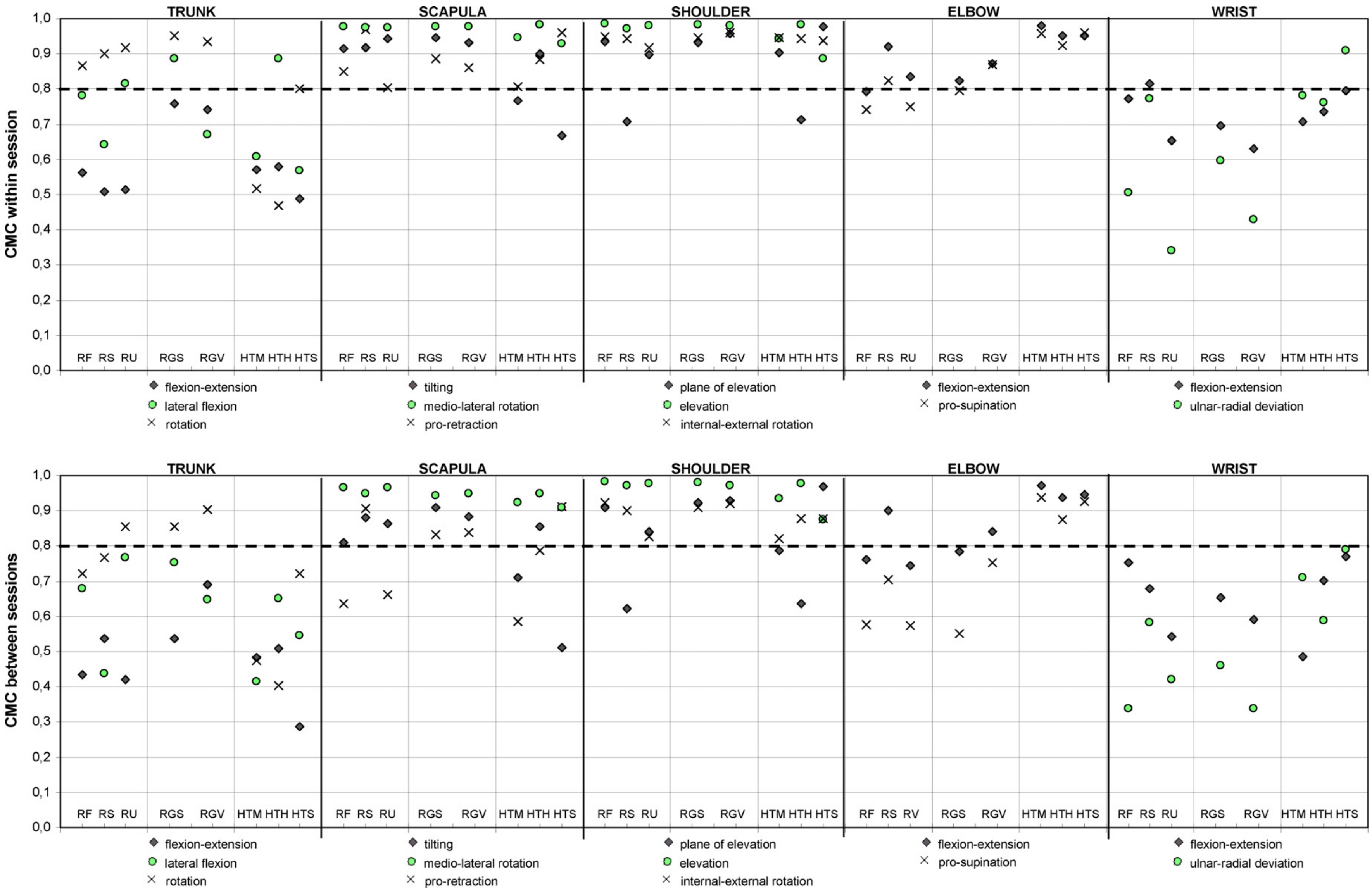

Fig. 3. Reliability of angular waveforms: within and between CMC per joint, for each upper limb task. RF: reach forwards; RS: reach sideways; RU: reach upwards; RGS: reach grasp spherically; RGV: reach grasp vertically; HTM: hand to mouth; HTH: hand to head; and HTS: hand to shoulder.

calculated joint angle was visualized as a function of time. Erroneous signals due to artefacts caused by marker-occlusion were not included in the statistical analysis. Temporal parameters (movement duration/speed) and joint angles at PTA were derived for every movement cycle of every task.

2.5. Statistical analysis

Reliability of the temporal parameters and joint angles at PTA was assessed with the intraclass correlation coefficient (ICC), with 95%CI, and the standard error of measurement (SEM) estimated from the square root of the mean square error term from the two-way ANOVA [24]. Within session reliability was calculated with $ICC_w(2,1)$ and SEM_w, based on single data; between session reliability with $ICC_b(2,k)$ and SEM_b, using averaged data [24].

Similarity of the angular waveforms was evaluated with the adjusted coefficient of multiple correlation (CMC) [25]. CMCs were computed for every child, from which median values were calculated. Similar to the SEM, the waveform measurement error was also calculated (σ) [26]. Within session errors (σ_w) were based on inter-trial waveform comparisons and reflect the intrinsic reliability of upper limb kinematics. Between session errors (σ_b) were calculated based on the inter-session comparison of all waveforms and reflect the extrinsic errors arising from various methodological sources. Within session errors were used as a reference level to which the extrinsic sources of error can be compared, and reported as the ratio of between to within errors [26].

3. Results

Information on within and between reliability coefficients can be found in Figs. 2 and 3. Full details are available as Supplementary Material. Within and between measurement errors are given in Tables 1 and 2.

3.1. Temporal parameters

Movement duration and speed were reliable within and between sessions (ICC_w 0.54–0.91; ICC_b 0.70–0.96). SEM for duration ranged between 0.05 and 0.19 s (SDD 0.14–0.53 s) and for speed between 0.02 and 0.05 m/s (SDD 0.08–0.28 m/s), with the highest SEM_w and SDD_w for HTH.

3.2. Joint angles at PTA

Within session ICCs were above 0.70 for all joint angles at PTA, during all tasks. Between session ICCs were higher than 0.60 for all tasks. Only for shoulder rotation and elbow pro-supination during RF and RU; and shoulder rotation and scapular pro-retraction during RGV, lower ICC_b-values were found.

Within session SEM-values ranged from 1.2° to 9.7° (SDD_w 3.4–26.9°). Trunk, scapula, shoulder, elbow angles at PTA, as well as wrist deviations had $SEM_w \leq 5°$ (SDD_w 3.4–14.3°) for all tasks (except elbow flexion for RF, shoulder elevation plane for HTM, HTH and shoulder elevation for HTM: SEM_w 5–7°; SDD_w 15.2–18.1°). Higher SEM_w were found for wrist flexion (SEM_w 5.2–9.7°; SDD_w 14.3–26.9°). Between session SEM-values were slightly higher, ranging from 1.6° to 10.2° (SDD_b 4.5–28.2°). For all reaching and reach-to-grasp tasks, $SEM_b \leq 5°$ were reported for trunk, scapula and shoulder angles in the coronal and sagittal plane (SDD_b 6.0–14.2°), except for the shoulder elevation plane and wrist flexion during reaching (SEM_b 4.1–8.1°; SDD_b 11.4–22.4°). Scapular pro-retractions had SEM_b between 5° and 7° (SDD_b 15.5–17.8°); shoulder rotations and elbow pro-supination showed $SEM_b \geq 7°$ (SDD_b 18.0–28.2°). For the gross motor tasks, $SEM_b \leq 5°$ were found for all trunk angles, scapular tilting (except HTH), scapular medio-lateral rotation and elbow flexion (SDD_b 4.5–13°). Scapula, shoulder and elbow angles in the transverse plane, as well as wrist angles had SEM_b-values from 5° to 9° for the gross motor tasks (SDD_b 14.9–23.9°).

3.3. Angular waveforms

Within session reliability was high for scapula and shoulder waveforms and elbow flexion for all tasks, and pro-supination for reaching and reach-to-grasp ($CMC_w > 0.80$). Between session CMCs were similar, though lower values were found for scapular pro-retraction and elbow pro-supination. Trunk and wrist waveforms were less reliable.

Between session errors ranged from 1.8° to 9.9°, with errors ≤5° for trunk and scapula waveforms and wrist deviations. Errors between 4° and 8° were found for the shoulder elevation plane and elevation during reaching and reach-to-grasp; and between 5° and 7° for elbow flexion during the reach-to-grasp and gross motor tasks. Error-ratios (σ_b/σ_w) were below 1.5 for trunk, scapula and shoulder waveforms during reaching (except for pro-retraction during RU) and for wrist and elbow waveforms during all but two tasks (RF, HTS). Scapular tilting, shoulder elevation plane and rotations had higher ratios, especially during the reach-to-grasp and gross motor tasks (1.3–2.4).

4. Discussion

The aim of this study was to establish the reliability of a protocol for UL-3DMA in children with HCP. Tasks were specifically selected to obtain a full representation of upper limb abilities of the hemiplegic child.

Results indicated good within and between session reliability for movement duration/speed for every task. High within session ICCs signified good reliability of the joint angles at PTA, and between session values showed good reliability over time. Lower between session ICCs were found for elbow pro-supination during reaching; and shoulder axial rotation during reaching and HTS. These joints also showed concurrent higher SEM_b. However, for wrist flexion, the higher SEM did not reflect the reported high ICC. This discrepancy could be attributed to the heterogeneity of the group, since larger between-subject variability affects the ICC towards higher values [24].

Good to excellent within and between session similarities of the angular waveforms were found for the shoulder during all tasks, for the scapula during reaching and reach-to-grasp, and for the elbow during the gross motor tasks. Trunk and wrist movements had lower within and between CMCs. Measurement errors >7° were reported for shoulder and elbow rotation, whilst errors <5° were reported for wrist deviations and the trunk. However, hemiplegic children generally use a rather fixed wrist position during task execution. As it is well known that the amount of joint ROM influences the CMC [27], the lower CMCs for the wrist should be interpreted with this in mind.

Schneiberg et al. [12] previously reported between session reliability during a reach-to-grasp task. They found somewhat higher measurement errors for elbow and shoulder flexion (SEM_b 5.3–6.3°) compared to our results for RGS (SEM_b 2.6–3.2°). However, this study also included children with quadriplegic and diplegic CP, and used a simplified biomechanical model for joint angle calculation. Mackey et al. [13] reported similar levels of reliability for shoulder and elbow flexion ($CMC > 0.90$), though lower values for shoulder and elbow rotations during HTH and HTM (CMC_b 0.49–0.74) compared to this study (CMC_b 0.82–0.94). Reid et al. [14] analyzed trunk, shoulder, elbow and wrist reliability during RF, RS, HTM and pro-supination. They reported moderate to high within session CMCs, but markedly lower between session reliability for shoulder and elbow angles (CMC_b 0.00–0.88 vs. CMC_b 0.58–0.98 in this study) and negative coefficients of determination for wrist angles. The higher levels of reliability found in our study might in part be ascribed to the thorough standardization. Differences in biomechanical model and analyzed tasks hinder further comparison of reliability results.

Knowledge on the magnitude of measurement errors is crucial to determine whether a measurement is reliable enough for clinical decision-making. Results of the current study showed that

Table 1
Reliability of joint angles at PTA and temporal parameters for the selected upper limb tasks.

A. Within session mean (SD), standard error of measurement (SEM_w) and smallest detectable difference (SDD_w)

	Reach forwards			Reach sideways			Reach upwards			Reach to grasp spherically		
	Mean (SD)	SEM_w	SDD_w	Mean (SD)	SEM_w	SDD_w	Mean (SD)	SEM_w	SDD_w	Mean (SD)	SEM_w	SDD_w
Temporal												
Duration	0.10 (0.19)	0.08	0.22	0.11 (0.25)	0.10	0.28	0.11 (0.21)	0.10	0.28	0.12 (0.27)	0.12	0.33
Speed	0.43 (0.11)	0.03	0.08	0.51 (0.11)	0.04	0.11	0.50 (0.12)	0.04	0.11	0.40 (0.12)	0.05	0.14
Trunk												
Flexion	3.5 (5.9)	2.4	6.8	−1.9 (6.8)	2.9	8.0	0.6 (6.3)	3.2	8.9	5.6 (6.4)	2.2	6.1
Lateral flexion	−6.7 (6.2)	2.1	5.8	4.2 (5.6)	2.4	6.6	−8.4 (7.3)	2.4	6.7	−5.7 (7.1)	1.3	3.5
Rotation	14.4 (7.4)	2.1	5.9	−19.8 (11.8)	3.5	9.6	13.2 (9.2)	2.8	7.9	16.5 (6.4)	1.7	4.8
Scapula												
Pro-retract	49.8 (8.0)	2.3	6.4	25.7 (7.9)	2.4	6.7	46.4 (9.7)	2.9	8.0	51.2 (7.5)	1.6	4.3
Med-lat rot	−27.5 (5.7)	2.4	6.5	−30.3 (6.3)	2.2	6.2	−36.9 (7.3)	3.0	8.2	−30.7 (5.1)	1.9	5.4
Tilting	−4.6 (6.2)	1.9	5.2	0.0 (7.0)	2.6	7.3	1.2 (6.3)	2.5	6.9	−2.6 (5.2)	1.2	3.4
Shoulder												
Elev plane	65.9 (8.8)	3.9	10.9	27.2 (12.5)	3.3	9.3	64.8 (10.6)	3.4	9.5	66.8 (8.4)	2.8	7.7
Elevation	−78.6 (7.2)	2.9	7.9	−79.4 (6.6)	3.6	10.1	−92.5 (8.1)	3.9	10.9	−80.9 (7.4)	2.8	7.8
Rotation	−45.6 (6.5)	2.7	7.3	−45.6 (9.8)	2.2	6.1	−46.9 (8.8)	2.4	6.7	−48.5 (6.4)	1.9	5.3
Elbow												
Flexion	49.8 (18.4)	5.8	16.2	37.3 (14.3)	4.9	13.6	44.1 (16.5)	4.4	12.1	52.7 (15.8)	4.6	12.9
Pro-sup	141.1 (13.0)	3.1	8.6	136.7 (7.0)	3.0	8.3	137.7 (11.0)	3.2	8.8	140.7 (11.5)	3.8	10.5
Wrist												
Flexion	23.3 (24.3)	9.6	26.7	26.6 (25.2)	6.0	16.7	24.5 (29.7)	5.5	15.3	25.9 (28.2)	9.7	26.9
Deviation	−7.1 (7.5)	3.3	9.1	−0.7 (8.2)	3.7	10.3	−8.3 (7.5)	3.6	9.9	−2.4 (9.3)	3.9	10.7

	Reach to grasp vertically			Hand to mouth			Hand to head			Hand to shoulder		
	Mean (SD)	SEM_w	SDD_w	Mean (SD)	SEM_w	SDD_w	Mean (SD)	SEM_w	SDD_w	Mean (SD)	SEM_w	SDD_w
Temporal												
Duration	0.12 (0.22)	0.14	0.39	0.09 (0.16)	0.09	0.25	0.10 (0.27)	0.19	0.53	0.92 (0.27)	0.08	0.22
Speed	0.37 (0.10)	0.04	0.11	0.46 (0.10)	0.04	0.11	0.59 (0.18)	0.10	0.28	0.47 (0.12)	0.04	0.11
Trunk												
Flexion	8.5 (8.0)	2.5	7.0	−3.0 (6.1)	2.4	6.6	−8.7 (5.1)	2.8	7.8	−3.1 (5.7)	2.0	5.7
Lateral flexion	−3.0 (11.6)	1.9	5.2	−0.3 (3.8)	1.8	5.0	−4.5 (4.0)	1.7	4.7	−2.7 (5.8)	2.2	6.1
Rotation	17.8 (7.0)	2.1	5.7	1.6 (3.7)	2.0	5.6	1.9 (5.6)	2.8	7.8	13.4 (7.0)	3.8	10.5
Scapula												
Pro-retract	49.0 (7.9)	1.8	4.9	40.2 (12.9)	2.9	8.0	27.4 (8.4)	4.3	11.8	59.7 (8.7)	1.9	5.3
Med-lat rot	−26.5 (6.2)	1.8	4.9	−24.3 (8.0)	3.7	10.3	−41.4 (7.7)	2.2	6.0	−15.6 (8.5)	2.3	6.5
Tilting	−0.5 (5.9)	1.7	4.6	−4.6 (5.5)	2.2	6.0	7.2 (8.9)	4.4	12.3	−8.4 (5.5)	1.2	3.4
Shoulder												
Elev plane	69.4 (9.0)	3.3	9.1	64.1 (20.3)	5.5	15.2	48.7 (11.0)	5.8	16.0	103.8 (11.1)	3.5	9.6
Elevation	−79.0 (8.5)	2.7	7.4	−57.1 (18.5)	6.5	18.1	−90.6 (12.0)	4.6	12.8	−40.7 (13.4)	4.2	11.5
Rotation	−55.2 (6.9)	1.9	5.2	−50.8 (8.8)	3.3	9.1	−56.8 (6.9)	3.5	9.6	−45.3 (8.9)	3.4	9.5
Elbow												
Flexion	50.5 (19.4)	5.0	13.9	131.2 (6.6)	3.9	10.8	111.8 (14.5)	3.7	10.1	100.6 (9.8)	3.0	8.3
Pro-sup	117.2 (23.3)	5.1	14.0	95.2 (24.7)	5.2	14.3	100.0 (34.3)	4.2	11.7	107.0 (21.4)	3.8	10.5
Wrist												
Flexion	11.2 (23.2)	7.4	20.5	34.3 (38.0)	7.2	19.9	38.9 (33.6)	7.1	19.8	56.4 (24.4)	5.2	14.3
Deviation	−7.8 (15.1)	4.8	13.4	−19.1 (11.4)	4.7	13.0	−15.8 (12.9)	4.9	13.7	−17.0 (11.9)	3.5	9.7

B. Between session mean (SD), standard error of measurement (SEM_b) and smallest detectable difference (SDD_b)

	Reach forwards			Reach sideways			Reach upwards			Reach to grasp spherically		
	Mean (SD)	SEM_b	SDD_b	Mean (SD)	SEM_b	SDD_b	Mean (SD)	SEM_b	SDD_b	Mean (SD)	SEM_b	SDD_b
Temporal												
Duration	0.98 (0.19)	0.07	0.19	1.10 (0.21)	0.07	0.19	1.08 (0.19)	0.05	0.14	1.15 (0.23)	0.13	0.36
Speed	0.44 (0.11)	0.03	0.08	0.53 (0.11)	0.04	0.11	0.50 (0.13)	0.04	0.11	0.41 (0.12)	0.03	0.08
Trunk												
Flexion	2.5 (6.0)	2.9	7.9	−2.0 (6.7)	4.6	12.7	−0.3 (7.1)	4.1	11.5	6.0 (7.0)	4.5	12.6
Lateral flexion	−6.7 (5.8)	3.2	8.9	4.1 (4.9)	2.4	6.6	−8.0 (6.5)	2.5	7.1	−6.3 (6.2)	3.0	8.3
Rotation	13.2 (8.4)	6.1	16.9	−18.6 (10.2)	6.3	17.5	13.5 (9.5)	7.3	20.2	16.9 (6.9)	3.2	8.8
Scapula												
Pro-retract	50.7 (7.7)	5.6	15.5	26.8 (7.5)	6.4	17.8	47.8 (8.7)	5.7	15.7	51.3 (8.0)	5.7	15.7
Med-lat rot	−27.0 (5.4)	4.0	11.2	−30.3 (5.3)	3.3	9.2	−35.2 (6.7)	3.5	9.8	−29.2 (6.2)	3.6	9.9
Tilting	−5.8 (7.0)	4.4	12.2	−0.1 (8.0)	4.6	12.6	0.2 (6.6)	4.1	11.5	−4.7 (6.6)	3.2	9.0
Shoulder												
Elev plane	67.1 (10.1)	6.9	19.0	26.6 (11.1)	5.6	15.5	65.0 (9.8)	4.1	11.4	66.2 (9.2)	4.6	12.7
Elevation	−77.1 (7.0)	3.4	9.4	−79.3 (6.3)	3.1	8.7	−91.2 (8.1)	2.9	8.1	−81.8 (7.8)	2.6	7.3
Rotation	−49.1 (9.1)	8.5	23.5	−48.9 (12.1)	8.7	24.1	−49.8 (9.9)	7.8	21.5	−48.7 (8.6)	6.7	18.6
Elbow												
Flexion	49.8 (17.1)	7.7	21.3	36.8 (14.2)	4.6	12.6	44.6 (15.6)	5.0	13.8	49,2 (17,8)	3.2	8.8
Pro-sup	142.7 (11.6)	9.6	26.5	137.1 (8.2)	8.5	23.7	140.3 (11.0)	8.7	24.1	140.0 (12.4)	10.2	28.2
Wrist												
Flexion	24.0 (23.2)	8.1	22.4	27.3 (23.8)	7.6	21.0	25.2 (28.6)	7.6	21.0	23.0 (26.5)	6.8	18.9
Deviation	−6.4 (6.9)	3.4	9.4	0.5 (6.6)	3.4	9.3	−6.4 (7.1)	2.2	6.0	−1.7 (8.8)	3.9	10.7

	Reach to grasp vertically			Hand to mouth			Hand to head			Hand to shoulder		
	Mean (SD)	SEM_b	SDD_b	Mean (SD)	SEM_b	SDD_b	Mean (SD)	SEM_b	SDD_b	Mean (SD)	SEM_b	SDD_b
Temporal												
Duration	1.16 (0.23)	0.15	0.42	0.90 (0.16)	0.08	0.22	1.00 (0.20)	0.12	0.33	0.87 (0.23)	0.08	0.22
Speed	0.39 (0.12)	0.05	0.14	0.47 (0.11)	0.05	0.14	0.61 (0.16)	0.07	0.19	0.49 (0.11)	0.04	0.11
Trunk												
Flexion	8.5 (8.3)	5.1	14.2	−3.4 (6.0)	4.7	13.0	−8.5 (5.4)	4.6	12.8	−3.3 (6.0)	4.7	13.0
Lateral flexion	−3.0 (10.0)	3.3	9.0	−1.4 (3.8)	2.8	7.8	−6.2 (4.4)	2.0	5.7	−1.2 (5.5)	3.2	8.9
Rotation	17.4 (7.6)	2.6	7.1	3.5 (5.9)	4.0	11.0	2.0 (6.0)	2.9	8.0	13.8 (7.8)	3.5	9.7
Scapula												
Pro-retract	50.6 (7.4)	5.9	16.4	41.0 (10.5)	5.8	16.2	24.8 (11.1)	7.8	21.7	59.3 (8.4)	8.0	22.3
Med-lat rot	−26.0 (5.3)	4.0	11.2	−21.2 (10.2)	3.3	9.2	−41.2 (7.2)	4.6	12.6	−18.0 (9.9)	4.0	11.1
Tilting	−1.8 (6.3)	2.9	7.9	−7.4 (8.3)	4.2	11.6	7.0 (14.3)	7.2	20.0	−9.1 (6.6)	4.5	12.6
Shoulder												
Elev plane	69.9 (9.1)	4.1	11.4	65.7 (19.9)	8.4	23.2	48.4 (11.1)	5.0	13.8	99.6 (12.2)	6.8	19.0
Elevation	−79.4 (8.0)	2.7	7.4	−53.6 (17.4)	4.7	13.0	−93.6 (11.2)	6.0	16.7	−44.7 (18.2)	5.1	14.2
Rotation	−56.7 (7.2)	6.5	18.0	−50.3 (10.0)	6.7	18.7	−56.9 (8.4)	6.3	17.5	−45.1 (11.0)	8.6	23.9
Elbow												
Flexion	50,4 (19,1)	4.8	13.4	132,1 (5,9)	1.6	4.5	108,2 (14,1)	4.3	11.9	104,9 (9,8)	3.6	9.9
Pro-sup	117.6 (24.1)	7.3	20.2	90.7 (23.4)	6.1	16.8	93.3 (32.1)	5.4	14.9	107.6 (22.5)	6.2	17.2
Wrist												
Flexion	12.6 (21.1)	6.4	17.7	33.4 (35.1)	9.9	27.5	40.5 (29.1)	4.9	13.5	52.1 (25.0)	5.3	14.8
Deviation	−6.3 (14.5)	4.3	11.8	−19.5 (10.3)	5.9	16.3	−19.1 (15.5)	6.2	17.1	−14.1 (11.0)	6.9	19.1

Mean, standard deviation (SD), standard error of measurement (SEM) and smallest detectable difference (SDD) are presented in degrees for the joint angles at PTA, in seconds for movement duration and meters/second for movement speed. SEM based on ANOVA.

Table 2
Reliability of the angular waveforms. Within session measurement error (σ_w), between session measurement error (σ_b) and the ratio ($r = \sigma_b/\sigma_w$) of the angular waveforms for the selected upper limb tasks.

	Reach forwards			Reach sideways			Reach upwards			Reach to grasp spherically		
	σ_w	σ_b	r	σ_w	σ_b	r	σ_w	σ_b	r	σ_w	σ_b	r
Trunk												
Flexion	2.5°	3.0°	1.2	3.7°	3.5°	0.9	3.2°	3.8°	1.2	1.7°	2.5°	1.5
Lateral flexion	2.4°	2.8°	1.2	2.4°	2.5°	1.0	2.5°	2.5°	1.0	1.4°	2.4°	1.7
Rotation	6.1°	5.3°	0.9	6.2°	5.6°	0.9	6.1°	4.7°	0.8	1.5°	2.9°	1.9
Scapula												
Pro-retract	3.4°	4.3°	1.3	3.2°	3.7°	1.2	2.9°	4.7°	1.6	1.9°	3.3°	1.8
Med-lat rot	2.6°	3.3°	1.3	3.4°°	3.5°	1.0	4.3°	3.8°	0.9	2.3°	3.4°	1.5
Tilting	2.8°	3.4°	1.2	2.6°	3.6°	1.4	2.8°	3.2°	1.1	1.2°	2.7°	2.1
Shoulder												
Elev plane	7.9°	7.6°	1.0	6.0°	6.7°	1.1	5.9°	6.5°	1.1	5.4°	6.2°	1.2
Elevation	4.2°	4.8°	1.1	5.9°	5.7°	1.0	7.5°	5.0°	0.7	4.0°	4.5°	1.1
Rotation	8.8°	8.6°	1.0	7.2°	7.9°	1.1	7.5°	8.0°	1.1	4.4°	6.9°	1.6
Elbow												
Flexion	6.7°	7.1°	1.1	8.7°	8.2°	0.9	8.7°	6.9°	0.8	4.8°	5.8°	1.2
Pro-sup	4.2°	7.9°	1.9	4.3°	4.7°	1.1	5.1°	7.5°	1.5	3.6°	5.4°	1.5
Wrist												
Flexion	9.8°	9.9°	1.0	8.2°	8.8°	1.1	10.0°	9.7°	1.0	6.0°	8.1°	1.3
Deviation	4.4°	4.6°	1.1	4.3°	4.5°	1.0	4.5°	4.5°	1.0	3.0°	4.5°	1.5

	Reach to grasp vertically			Hand to mouth			Hand to head			Hand to shoulder		
	σ_w	σ_b	r	σ_w	σ_b	r	σ_w	σ_b	r	σ_w	σ_b	r
Trunk												
Flexion	2.5°	4.0°	1.6	2.4°	3.3°	1.4	2.6°	3.9°	1.5	1.8°	3.4°	1.9
Lateral flexion	1.8°	2.9°	1.6	1.4°	2.3°	1.7	1.6°	2.3°	1.5	1.9°	2.9°	1.5
Rotation	1.8°	3.0°	1.7	1.5°	2.6°	1.7	2.0°	3.3°	1.6	2.4°	2.5°	1.0
Scapula												
Pro-retract	1.9°	4.4°	2.3	2.0°	3.2°	1.6	3.0°	4.5°	1.5	1.8°	4.2°	2.4
Med-lat rot	2.2°	3.7°	1.7	2.6°	3.0°	1.1	2.3°	3.9°	1.7	2.2°	2.9°	1.3
Tilting	1.6°	3.0°	1.8	1.3°	1.8°	1.4	2.5°	4.4°	1.7	1.3°	3.0°	2.4
Shoulder												
Elev plane	5.2°	6.6°	1.3	6.0°	8.3°	1.4	5.4°	7.1°	1.3	5.9°	9.4°	1.6
Elevation	3.8°	4.6°	1.2	4.6°	5.3°	1.1	4.2°	6.5°	1.6	3.8°	3.8°	1.0
Rotation	4.0°	7.3°	1.8	4.2°	8.1°	1.9	4.5°	5.8°	1.3	5.7°	9.3°	1.6
Elbow												
Flexion	5.2°	5.8°	1.1	5.4°	6.1°	1.1	5.4°	6.7°	1.2	4.1°	5.1°	1.2
Pro-sup	5.7°	7.5°	1.3	6.6°	7.3°	1.1	4.7°	5.7°	1.2	3.9°	6.8°	1.7
Wrist												
Flexion	6.6°	8.1°	1.2	6.7°	8.9°	1.3	7.2°	7.3°	1.0	6.0°	7.1°	1.2
Deviation	4.9°	5.3°	1.1	3.7°	4.7°	1.3	3.8°	5.3°	1.4	2.6°	4.1°	1.6

Within and between session measurement error (σ_w and σ_b) are presented in degrees for the angular waveforms.
σ based on Schwartz et al. [26].

measurement errors of joint angles at PTA, and the waveforms were ≤5° for most joints. However, between session errors were higher for shoulder rotations, elbow pro-supination and wrist flexion (SEM_b 5–10°; σ_b 5–10°), and scapular pro-retractions at PTA (SEM_b 5–9°). These higher between session errors compared to low within session errors for the shoulder, scapula and elbow might point to palpation inaccuracies or differences in marker placement. The calculation of elbow and shoulder joint centers and axes based on functional or optimization methods could aid in improving the reliability of joint kinematics, as these do not rely on accurate palpation [28]. Available literature on the measurement errors of upper limb kinematics in children with HCP is scarce and further studies will need to determine whether the reported errors are low enough compared to the expected effect size after upper limb intervention.

This study additionally established the reliability of scapular movements, which has not been reported before in children with HCP. Results suggested that the scapula can be measured reliably, with measurement errors <5° for tilting and medio-lateral rotation and between 5° and 8° for pro-retractions. As the importance of scapular kinematics in shoulder movements has been well established in children and adults [15], it should be taken into account when evaluating upper limb motor performance. Furthermore, several muscles that are potential targets for BTX-intervention have their origin/insertion on the scapula (e.g. biceps, triceps, pectoralis minor, teres major ...) [29], adding to the importance of a thorough understanding of scapular kinematics for clinical practice.

The current study generally showed good to high levels of reliability of the proposed protocol to evaluate upper limb kinematics in children with HCP, providing a sound base for its clinical application. Future clinical implementation additionally requires the establishment of the discriminative ability. This necessitates the construction of a proper database with age-related standards for TDC. Knowledge on how TDC perform the selected tasks will facilitate the identification of pathological movements and increase our understanding of compensatory strategies seen in children with HCP. In the end, these insights will contribute to the clinical decision-making process for upper limb interventions. The conversion of results from the UL-3DMA into useful information at the level of muscle functions and bony structures [30] is a challenging process and remains a necessary future step.

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Conflict of interest statement

The authors report no financial or personal relationships with other people or organizations that could inappropriately influence their work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2011.01.011.

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