Promoting Functional and Independent Siting in Children with Cerebral Palsy Using the Robotic Trunk Support Trainer

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Abstract—Seated postural abilities are critical to functional independence and participation in children with cerebral palsy, Gross Motor Functional Classification System (GMFCS) levels III-IV. In this proof-of-concept study, we investigated the feasibility of a motor learning–based seated postural training with a robotic Trunk-Support-Trainer (TruST) in a longitudinal single-subject-design (13y, GMFCS IV), and its potential effectiveness in a group of 3 children (6-14y, GMFCS III-IV). TruST is a motorized-cable driven belt placed on the child’s trunk to exert active-assistive forces when the trunk moves beyond stability limits. TruST-intervention addresses postural-task progression by tailoring the assistive-force fields to the child’s sitting balance to train trunk control during independent short-sitting posture. TruST-intervention consisted of 2 training blocks of 6 2-hour sessions per block (3 sessions per week). Pelvic strapping was required in the 1st block to prevent falls. As primary outcomes, we used the modified functional reach test, gross motor function measure-item set (GMFM-IS), Box & Blocks, and postural kinematics. After TruST-intervention children did not require pelvic strapping to prevent a fall, improved trunk stability during reaching (baseline = 5.49cm, 1week post-training = 16.38cm, 3mos follow-up = 14.63cm, p < 0.001) and increased their sitting workspace (baseline = 127.55cm², 1week post-training, = 409.92cm², 3mos follow-up = 270.03cm², p < 0.001). Three children also improved in the GMFM-IS. In summary, our novel robotic TruST-intervention is feasible and can effectively maximize functional independent sitting in children with CP GMFCS III-IV.

Index Terms—Cerebral Palsy, Sitting, Reaching, Intervention, Robotics, Force Field.

I. INTRODUCTION

Cerebral palsy (CP) refers to a group of permanent disorders after brain damage that result in impaired development and control of movement and posture [1]. CP is the most common childhood physical disability—2.0-3.5 per 1000 births—with a costly lifetime care [2], [3]. Children classified as level III by the Gross Motor Function Classification System (GMFCS) require wheelchairs to travel long distances and those with GMFCS IV need wheelchairs in most settings. Moreover, they often require adaptive seating to secure trunk-pelvic stability. The absence of ambulation and poor seated functional independence in CP are associated with reduced societal involvement and survival across age [2], [4]-[7]. Thus, a therapy designed to improve the sitting control abilities of this CP subpopulation is critical to promote independent functions, an active physical life, and community participation.

During the first 8mos of life, infants learn how to control the segments of the trunk, from head to hips, to achieve unsupported sitting [8]. In children with CP and GMFCS III-IV however, the neural insult disrupts the segmental control progression of the trunk [9], [10]. These children have trunk control deficits at low-thoracic and lumbar regions that consequently disrupt seated posture and reaching control. However, when the torso is supported above the more-affected trunk sub-region, posture and reaching improve substantially [10]—which suggest that an external support targeting the most-impaired trunk region can be of high value to train their postural and reaching abilities. A recent randomized controlled trial compared conventional therapy with a home-based activity training using a rigid system supporting the impaired trunk segment [11]. The segmental training resulted in short-term balance improvements; although no functional gains were observed. A potential reason for the lack of functional improvements is that the segmental training was not based on motor learning principles—goal-oriented movements, intensive repetitions and motor variability—which have been shown to be highly effective in CP trainings [12]-[15]. Additionally, task-progress is critical in activity-based therapy to drive neural plasticity and long-term functional benefits [16], [17].

Robotics in CP can promote task-specific practice [18], [19]. Here, we use a Trunk-Support-Trainer (TruST) to deliver postural task-oriented training in children with CP. TruST is a motorized cable-driven belt placed on the child’s most-impaired trunk region. It creates a circular force field that corresponds to the child’s sitting stability boundaries. The goal is to supplement the child’s motor efforts when the trunk moves beyond the stability limits through active-assistive forces by modulating the wire tensions [18], [20], [21]. We have tested TruST in a study with healthy adults that included experimental and control groups [21]. The force field diameter was tailored to the person’s postural ability—point at which the participant lost sitting balance during maximal reaching. TruST-force field was equivalent to 10% of the individual’s weight at the point of sitting imbalance. After a single 30min-training session, adults increased the displacement and rotation of the lumbar region while practicing a fine-motor task during unbalanced sitting. We have also shown that TruST-force fields can expand the sitting workspace of people with spinal cord injury [22].

In the current proof-of-concept study, we investigate tolerance, feasibility, and potential effectiveness of TruST-intervention in children with CP and GMFCS III-IV. We test if these children can acquire functional and independent sitting—here, functional indicates the child’s ability to perform goal-oriented activities; and independent, refers to the child’s ability to sit safely without any type of assistance.
II. METHODOLOGY

A. Clinical Features of Children

Clinical and functional details of the sample are included in Appendix I. We recruited 4 children with bilateral CP (Mean age = 11 ± 1.5yrs), GMFCS III-IV (quadriplegia = 3 and spastic diplegia = 1), and trunk control deficits at the low-thoracic region (T9-T12), according to the Segmental Assessment of trunk control (SATCo) [23]. The GMFCS functionally classified all children as wheelchair users [6]. The Manual Ability Classification System (MACS) indicated that children had limited manual abilities [31]. The GMFM-Item Set (GMFM-IS) revealed major sitting control limitations [26]. Three children could not maintain independently short-sitting posture on a bench more than 10 seconds. However, all children had severe postural alignment deficits during independent sitting (Movie 1) and could not perform goal-oriented tasks without assistance (Movie 2). Children met the following inclusion criteria: (1) SATCo: 3-4; (2) ability to perform simple reaching tasks (grasping was not required); and (3) cognitive capacity to follow basic verbal instructions (i.e. “do not put your hands on your lap” or “follow and reach the ball”). The exclusion criteria were: (1) fixed vertebral deformities (scoliosis >40° and/or kyphosis >45°); (2) spinal arthrodiesis; (3) severe dyskinesia—inability to move without loss of balance; (4) chemodenervation techniques, surgery, or antispastic medication administered 3mos before the study.

B. Study Design

Approval for this study was obtained by the IRB for Human Research at Columbia University (Protocol# AAAQ7781). Families found information about the study on flyers and contacted the research team. If children met the inclusion criteria, parents signed the informed consent and children verbally assented to participate. TruST-intervention comprised 2 training blocks (12 sessions in total) divided into six 2hour-sessions spread across 2 weeks (3 sessions per week). In the 1st training block, children used pelvic strapping to prevent falls. Data from our single-subject study showed potential to remove the strapping system at the 5th or 6th session. Thus, children received TruST-intervention without pelvic strapping (i.e. independent sitting) during the entire 2nd training block.

We first examined the feasibility of TruST-intervention in a 6-month multi-phase (A-B-A) single-subject-study in a child with CP, GMFCS IV, and impaired trunk control (SATCo = 4). We collected five baselines across two weeks to establish measurement stability of clinical and kinetic data and to account for potential variability and learning effects due to test practice [27]. We measured short-term postural and reaching improvements 1week post-training. This study was critical to refine TruST-intervention and decide when to remove the pelvic straps to further train children during independent sitting.

After the single-subject study, we conducted a 9mos-longitudinal group study on three children with CP and GMFCS III-IV. We collected two baseline sessions and measured short-term (1week post-training) and long-term (3mos follow-up) postural and reaching improvements after TruST-intervention. All children consistently followed the same school, home, and therapeutic regimes throughout the study to account for their effect on the post-training assessments [27].

C. Motor Behavior and Kinematic Outcomes

The GMFM-IS was used to quantify changes in gross motor function [26]. The Box & Block test was used to assess hand dexterity and determine the more-affected hand [28]. And the Modified Functional Reach Test (forward direction) was used to measure trunk stability while reaching [29].

After the single-subject study, we observed improvements in the child’s trunk stability limits in all directions. Thus, we designed the postural star-sitting test for our group study, which provided information on the children’s sitting workspace area (cm²) [22]. Similar to the star excursion balance test [30], in the postural star-sitting test, the child performs maximal trunk excursions following 8 lines that extend from a center point and are 45° from one another. The 8 lines form a star-shaped grid. The examiner uses a ball to encourage and guide the child during the execution of the trunk movements (Fig. 1).

We examined the static, active, and proactive postural dimensions of the Seated Postural & Reaching Control Test (SP&R-co)—a tool validated for children with CP [31]. Static, active, and proactive postural dimension tests require children to maintain upright sitting during 10s, while rotating the head 90° left and right to visually track a toy, and during reaching, respectively [32]. During proactive testing, children had to perform fast and accurate pointing reaches to a toy placed at maximum reaching distance with the more- and less-affected hands. As per the SP&R-co test, static, active, and proactive dimensions are examined with external support at the impaired trunk region. Thus, TruST was programmed to provide static support at the low-thoracic region during the SP&R-co test.

Postural and reaching kinematics were used to examine the modified functional reach test, postural star-sitting test, and the postural control dimensions of the SP&R-co test.

III. ROBOTIC TRUSTR-INTERVENTION

TruST system provides assist-as-needed forces to the child’s torso while practicing goal-oriented movements (Fig 1A). The algorithm recreates a circular planar force-tunnel around the trunk, based on the child’s maximum trunk excursion during the modified functional reach test.

TruST-forces remain unchanged if the child is inside the force field boundaries—area of stable sitting control. However, when the child moves the trunk beyond the predefined circular force field, TruST delivers assistive-forces toward the stability boundaries but not to the center (Fig. 1B). This configuration promotes active postural recovery to fully restore sitting. TruST-force field was equivalent to 10% of the child’s body weight and was systematically adjusted to the child’s seated trunk stability. TruST-force field was progressed across training sessions based on the modified functional reach test to implement postural task-progression during the training. Appendix I includes the motor learning-control principles and the TruST-intervention algorithm applied for training purposes.
Eq. (2) shows the $6 \times 1$ force/moment matrix, where $F_x$ and $F_y$ are the desired transverse forces computed by the force-tunnel controller (discussed in next section). $F_z, M_x, M_y,$ and $M_z$ are constrained using inequalities, to allow to solve Eq. (1) for tension values within the inequality constraints. For planar forces, we solve for $F_x$ and $F_y$ while satisfying constraints for other components. From a mathematical perspective, there are infinite solutions since we have an under-determined system. Thus, we apply an optimization function to ensure that the forces are determined within the desired limits, and the tensions are not discontinuous from the values at the previous time instance. The function minimizes deviations between $T$ (current tension) and $T_p$ (tension values at previous time instances) to allow for continuity in cable tensions defined as follows.

$$
\min f(T) = \frac{1}{2} (T - T_p)^T (T - T_p)
$$

$$
(4)
$$

B. Controller

The controller is divided into high- and low-level. The high-level controller consists of a force tunnel controller that creates a virtual force field at a specified radius around the patient’s trunk in the transverse plane. The center of the lower trunk is obtained by using a motion capture system and by computing the estimated centroid of the left and right lateral points on the trunk belt. When the centroid is detected to be outside a specified radius, a perpendicular force $F$ is calculated and applied towards the circular boundary. $F$ is defined by the direction $\vec{n}$ and force magnitude $k, 10\%$ body weight.

$$
F = F_p = k(\vec{n})
$$

$$
(5)
$$

The corresponding tension values are determined by solving Eq. (1) for tension values within the inequality constraints, at 200Hz. The low-level controller achieves the desired tension at 1kHz in force control mode, using a feedback and feedforward term. To achieve a desired tension, a specific current is provided to the motors. This is relative to a voltage (Eq. 6) calculated using a pre-measured motor constant, $K_M$, relating voltage and tension, an open-loop feedforward term, $T_{FF}$, and a closed-loop PID-based feedback term, $T_{FB}$. The PID was re-tuned to result into a quicker response during the postural training.

$$
V = K_M(T_{FF} + T_{FB})
$$

$$
(6)
$$

IV. Data Reduction

Kinematic data was smoothed with a zero time-lag 4th-order Butterworth filter at 4Hz-cutoff. Rotations were computed as inter-segmental angles, following the right-hand convention with an Euler sequence X-Y’-Z’’: flexion(-) / extension(+).
around x-axis (+forward), right-lateroflexion (+) / left-lateroflexion (-) around y-axis (+rightwards), and left-rotation (+) / right-rotation (-) around z-axis (+upward). The upper body was modeled as a 6 linked-segment system: head, upper-thorax, lower-thorax, pelvis, and upper limbs. COM data of segments and upper body was based on anatomical landmarks and anthropometrics published in [34].

MATLAB (R2017b, Mathworks, 2017) was used for processing kinematic data. We computed the maximum trunk excursion (cm) during the modified functional reach test. In the postural-star-sitting test, we collected the extreme points of the 8 maximum trunk excursions to define the sitting workspace area (cm²) with the in-built MATLAB function polyarea(x,y). We computed the absolute summation of upper body COM displacements (cm) across x-y-z axes. Postural orientation was estimated as the averaged angular motion of each segment across planes. Angular rotations across planes were computed by subtracting absolute maximum and minimum angles. Total angular motion was calculated as the absolute summation of angles. The SD of angles was used as a measurement of postural variability. We also computed reaching-related kinematics to characterize performance of arm movements—in the proactive dimension test. Kinematics were normalized to the maximum distance at which the toy was presented (i.e. maximum reaching distance). Reaching onsets and offsets (R\text{ONSET} and R\text{OFFSET}) were defined as 5% of maximum reaching peak velocity. Reaching duration was the time between R\text{ONSET} and R\text{OFFSET}. Reaching path was the distance covered by the arm during the reach. Reaching smoothness was based on trajectory (straightness score) and acceleration profiles (Normalized Jerk Score, NJS) of reaches. Straightness score is the ratio of the arm path length divided by the shortest linear vector—values closer to one represent straighter reaches and thus, greater level of arm control. A decrease in NJS is indicative of improved arm motion smoothness in children with CP [35].

V. STATISTICAL ANALYSIS

Data analyses were carried out using SPSS (IBM, version 22). In the single-subject-design study, we applied a distribution-based approach to explore and interpret the data based on relative %changes, Standard Error of Measurements (SEMs), and Minimum Detectable Changes (MDCs). In the single-subject-design study, only postural/reaching control changes that met the MDC or 50\% changes were interpreted as a substantial change or trend toward motor improvement, respectively (Appendix I). We hypothesized that functional and postural and reaching kinematic improvements would confirm feasibility of TruST-intervention and justify our group study.

In the group study, the alpha rate was set at 0.05. Kinematic angles identified as extreme outliers (values three times greater than the interquartile range) were considered abnormal and removed from further analysis. Data normality was examined with Shapiro-Wilk test and visual Q-Q plots. Normality and repeated measures ANOVA assumptions were violated in most instances. Furthermore, data were highly variable and suitable for a trial-by-trial analysis. Thus, we applied a Generalized Estimating Equation (GEE) to analyze events-in-trials following a repeated-measures procedure with children as clusters and training/evaluation sessions as the within-subject variable with a linear model. A model-based estimator was used, and an independent covariance structure was specified as correlation matrix based on the quasi-likelihood under independence criterion (QIC) goodness of fit coefficient—which is recommended in small sample sizes. Follow-up post-hoc tests were conducted to analyze significant effects with sequential Holm-Bonferroni adjustment to increase statistical power while controlling the familywise type error.

VI. RESULTS

A. Single-Subject-Design Study

The child progressed from not being able to sit independently at baseline to being able to sit on the bench without pelvic strapping and perform bimanual reaching tasks during the 2nd training block (Movie 2).

GMFM-IS. After TruST-intervention, the GMFM-IS score changed from 45.6 to 47.9 (Appendix 1). The child improved trunk rotations over his more-affected hemi-body in sitting and reached higher distances in a 4-point position (i.e. quadruped posture). In assisted stance, the child could raise his foot 2s post-test compared to 1s pre-test. During walking, the child required assistance of one hand instead of two hands.

Box & Block Test. The child improved hand dexterity (i.e. number of blocks transported over the partition) after TruST-intervention with the less-affected hand (baseline = 28, 1week post-training = 32) and more-affected hand (baseline = 4, 1week post-training = 7).

Modified Functional Reach Test. Compared to baseline (6cm), the child improved trunk stability while reaching by ∆128% (14cm) after the 1st training block in sitting with pelvic strapping, and by ∆233% (21cm) after the 2nd training block during unsupported sitting (1week post-training).

Static Postural Dimension Test. The child improved upright sitting stability with a decrease of ∆58% in upper body COM excursion (baseline: Mean = 26.7 ± 7.6cm, MDC = 7.4cm; 1week post-training: Mean = 11.3cm), ∆41% in head displacement (baseline: Mean = 40.4 ± 7.6cm, MDC = 10.1cm; 1week post-training: Mean = 23.93cm) and ∆40% in upper-thorax displacement (Baseline: Mean = 25.3 ± 3.9cm, MDC = 9.1cm; 1week post-training: Mean = 15.3cm).

Active Postural Dimension Test. The child substantially reduced by ∆47% upper body COM excursions during head rotations to the more-affected hemi-body (baseline: Mean = 22.0cm ± 1.9, MDC = 11.9cm; 1week post-training: Mean = 11.6cm ± 2.3cm). Trunk rotations also decreased (Fig. 3 A-C).

Proactive Postural Dimension Test. Reaches with the more-affected hand were kinematically analyzed. TruST-intervention had a different impact on postural and reaching control depending on the direction of the reach: contralateral (arm crossing midline to the opposite hemispace) or ipsilateral (arm in the same hemisphere of the reaching arm). Contralateral reaches were characterized by shorter durations (baseline: Mean = 0.25, SE = 0.02, MDC = 0.03; 1week post-training:
Improvements after TruST 2. They improved sitting control 1 week post-training (Movie 3), as observed by the child’s motor ability to rotate the trunk and reach in sitting. However, the improvement returned to baseline values at the 3mos follow-up. Child 04 demonstrated short-term and long-term gait improvements, as indicated by the GMFM-IS when the child had to walk more than 10 steps with one-hand assistance (Movie 4).

**Box & Block Test.** As a group, children did not significantly improve hand dexterity (Wald $\chi^2 = 1.85$, $P = 0.17$) after TruST-intervention.

**Modified Functional Reach Test.** As shown in Fig. 4, children acquired greater trunk stability limits at the end of each training block (Wald $\chi^2 = 41.63$, $P < 0.001$) and after TruST-Intervention (Wald $\chi^2 = 36.86$, $P < 0.001$) compared to baseline (Mean = 5.5 ± 1.4cm, 95%CI: 2.7-8.3). They improved their trunk stability limits after the 1st training block (Mean = 12.5 ± 0.5cm, 95%CI: 11.5-13.5, $P < 0.001$) and 2nd training block (Mean = 16.4 ± 1.7cm, 95%CI: 13.1-19.6, $P < 0.001$). Similarly, children showed significant improvements 1 week post-training (M = 15.9 ± 0.6cm, 95%CI: 14.7-17.2, $P < 0.001$) that were retained at the 3mos follow-up (M = 14.6 ± 1.3cm, 95%CI: 12.0-17.3, $P < 0.001$).

**Postural Star-Sitting Test.** As shown in Fig. 5, children improved volitional trunk control in the postural star-sitting test (Movie 5). They increased their sitting workspace after each training block (Wald $\chi^2 = 41.63$, $P < 0.001$) and TruST-intervention (Wald $\chi^2 = 49.35$, $P < 0.001$). Children significantly expanded their sitting workspace area after the 2nd block (Mean = 409.9 ± 130.1cm², 95%CI: 154.8 – 665.0, $P < 0.001$).

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**GMFM-IS.** Two out of the 3 children experienced functional improvements in the GMFM-IS after TruST-intervention (Appendix I). Child 03 improved sitting control 1 week post-training (Movie 3), as observed by the child’s motor ability to rotate the trunk and reach in sitting. However, the improvement returned to baseline values at the 3mos follow-up. Child 04 demonstrated short-term and long-term gait improvements, as indicated by the GMFM-IS when the child had to walk more than 10 steps with one-hand assistance (Movie 4).
0.001) with respect to baseline (Mean = 127.6 ± 61.1 cm²; 95% CI: 7.9-247.2). Furthermore, this expansion in sitting workspace area remained 1 week (Mean = 395.3 ± 48.3 cm²; 95% CI: 300.7-490.0, \( P < 0.001 \)) and 3 mos post-intervention (Mean = 270.0 ± 30.4 cm²; 95% CI: 210.49-329.56, \( P < 0.001 \)).

**Static Postural Dimension Test.** Children displayed the typical hyperextended head-trunk posture found in children with CP that present with severe trunk control deficits (Movie 1). After TruST-intervention, children showed steady sitting posture (Wald \( \chi^2 = 1567.78, P < 0.001 \)), as determined by a reduction in upper body COM displacement 1 week post-training (\( P < 0.001 \)). However, this reduction returned to similar baseline values after 3 mos (Table 1).

There was a specific-training effect in lower-thorax orientation during sitting (flexion-extension plane) (Wald \( \chi^2 = 16938.65, P < 0.001 \)), which was the most-impaired region across children. Also, children improved upper- and lower-thorax alignment during sitting after TruST-intervention (Fig. 6).

**Active Postural Dimension Test.** Unlike in our single-subject-study, not all children were able to reduce the excessive upper body COM excursions during head rotations. Nonetheless, they reduced upper-thorax variability while rotating the head to the more-affected hemibody 1 week post-training (Mean = 2.20 ± 0.53°, 95% CI: 1.17-3.24) and at 3 mos follow-up (Mean = 2.34 ± 0.58°, 95% CI: 1.21-3.47) compared to baseline (Mean = 4.49 ± 0.52°, 95% CI: 3.46-5.51). This was also true for head rotations to the less-affected hemibody 1 week post-training (Mean = 2.12 ± 0.29°, 95% CI: 1.55-2.68) and at 3 mos follow-up (Mean = 2.18 ± 0.60°, 95% CI: 1.00-3.36) relative to baseline (Mean = 4.79 ± 0.81°, 95% CI: 1.55-2.68).

**Proactive Postural Dimension Test.** Children improved posture and reaching control with the less-affected hand (Fig. 7). In ipsilateral reaches, upper body COM excursions remained similar after training blocks, 1 week post-training, and 3 mos follow-up. In contralateral reaches however, where the
simultaneous coordination between the trunk and arm is highly demanding, children reduced the amount of upper body movements while reaching (Wald $\chi^2 = 222.93, P < 0.001$). They decreased upper body COM excursions 1 week post-training (Mean = 6.54 ± 0.79, 95% CI: 4.98-8.10, $P = 0.001$) and at 3 mos follow-up (Mean = 5.56 ± 0.93, 95% CI: 3.74-7.38, $P < 0.001$) compared to baseline (Mean = 9.52 ± 1.27, 95% CI: 7.02-12.01). Ipsilateral reaches were characterized by shorter durations (Wald $\chi^2 = 37.84, P < 0.001$), reduced distance (Wald $\chi^2 = 7.85, P = 0.02$), straighter paths (Wald $\chi^2 = 9.30, P = 0.01$), and smoother trajectories (Wald $\chi^2 = 20.98, P < 0.001$). Similarly, contralateral reaches had shorter durations (Wald $\chi^2 = 23.67, P < 0.001$), reduced distance (Wald $\chi^2 = 8.61, P = 0.014$) and straighter paths (Wald $\chi^2 = 17.90, P < 0.001$).

**VII. DISCUSSION**

Our single-subject-study showed that TruST-intervention is feasible in a child with CP, GMFCS IV, and with segmental trunk control deficits. The child complied with the full length of TruST-intervention and tolerated the level of intensity without adverse effects. The child improved postural and reaching control, gross motor functions, and acquired independent sitting after the motor learning-based training with postural task-progression via TruST-force fields. Moreover, our group study demonstrated that TruST-intervention can be effective to promote independent short-sitting posture and to maximize trunk and reaching control in children with CP, GMFCS III-IV. The absence of postural and reaching changes during the two weeks-baseline in our single-subject-study (when the child received his usual therapeutic regime) and the timely changes observed in our group study demonstrate that the motor improvements are likely due to TruST-intervention.

Conventional therapies to improve postural sitting include muscle strengthening, neurodevelopmental treatment (NDT), functional electrical stimulation, and hippotherapy. However, studies conducted on children with CP and GMFCS IV report minimal improvements and children do not acquire independent sitting. Only hippotherapy may enhance postural sway, but results are inconclusive [13],[36]–[38]. However, research has shown that similar motor learning and control principles to those applied in TruST-intervention are highly effective during functional therapy in CP. Constrained Induced Movement Therapy (CIMT) [12] and Hand–Arm Bimanual Intensive Training (HABIT) [39] apply structured goal-oriented trainings characterized by repetition, intensity, motor variability, and task-progression to improve upper extremity functions in children with hemiplegic CP. Similarly, HABIT including Lower Extremity (HABIT-ILE) improves functional performance of lower extremities in children with bilateral CP while applying similar intensive learning-based principles [40].

There exist a great diversity of robotic platforms to assess and train posture [41] such as FASTRAK—a combined stationary instrumented bicycle and virtual reality system—, Spiderbot—a cable-driven system without wheels or base that provides support during mobility and balance training—, KineAssist—a robotic platform that provides partial body weight support and postural torques on the torso via trunk and pelvic mechanisms—and biofeedback-based balance platforms (e.g. eBaVir or AMBA) [42]–[45]. Nonetheless, some of these systems have not been tested in CP, just train postural control in standing, or demand a high level of balance from users (i.e. pelvic and lower extremity control) that children with CP, GMFCS III-IV, do not have. Emerging research now targets this CP sub-population. For example, new IMU technology (e.g. ENLAZA) combined with videogames successfully engage and train head control in seated children with CP [46].

TruST creates a dynamic robot-child-clinician interface within a motor learning paradigm to train seated postural and reaching abilities in children with bilateral CP. TruST implements postural-task progression via force fields to account for trial-error practice and haptic-feedback that are dependent upon the child’s trunk position and balance control. A study with adults showed that applying robot-mediated haptic-guidance and trial-error practice during a motor timing task activate error-detection (cerebellum-angular gyrus) and memory consolidation (caudate nucleus and parahippocampal gyrus) brain networks [47]. We believe these brain areas might also be involved in the long-lasting motor gains observed with TruST-intervention after the repetitive practice of goal-oriented postural tasks via “assist-as-needed” force fields.
TruST displays online visual feedback to the clinician on trunk movements (i.e. belt position), explicitly targeting postural control strategies within, at, and beyond the child’s sitting stability boundaries. In the design of the TruST-forces, we considered the performance-learning paradox whereby the continuous and regular application of augmented feedback only improves motor performance during training, but not in the long term due to feedback dependency [48]. Thus, the intensity of the “assist-as-needed forces” matched 10% of the child’s body weight. When the child was within the sitting stability boundaries, TruST-force field was inactive and the child only experienced task-intrinsic sensorimotor feedback during postural and reaching movements [15]. Only when the trunk was at or beyond the force field boundaries, TruST-forces acted on the trunk to maintain sitting steady or train postural recovery.

Considering the GMFM minimum clinically important difference, two children (03 and 04) showed a medium effect size change (1 point) and one child (01) demonstrated a large effect size change (2 points) after TruST-intervention [49], [50]. Child 04, who had CP, GMFCS III, and impaired trunk control, but the ability to sit independently, improved gait after TruST-intervention, according to the GMFM-IS. This finding is in line with previous research showing that trunk control and early sitting acquisition (< 2yrs) predict more reliably gross motor functions and walking abilities than spasticity, muscle strength, selective control, or age [51], [52]. The modified functional reach test determined that children improved sitting balance [53]. In baseline, children could reach no further than 6cm, but achieved a maximum trunk excursion of 16cm after TruST-intervention. There is not a MDC established yet for the modified functional reach test in CP; however, the improvements found were significantly higher than the 3.7cm MDC set for stroke [53]. The postural star-sitting test measures the 360º area of stable sitting control, which was severely limited in our sample of children. Children tripped their sitting workspace area 1 week post-training and doubled it at 3mos follow-up. Note however, that child 04 (GMFCS III) did not show much of a difference in sitting workspace after the 1st training block. Hence, greater improvements in sitting workspace could have been expected after TruST-intervention, if the pelvic strapping had been removed earlier in the training.

Children improved static, active, and proactive postural control, which are modulated by different neural and musculoskeletal mechanisms [54]. Children obtained a more vertically static alignment of the impaired lower-thorax during sitting. Static posture requires prolonged low-level neck-torso muscle coactivations [55]. It is likely that children improved at different static muscle control levels such as i) antigravity muscle extensor control mediated by force-related sensory feedback (Ib afferents), ii) α-motoneurons and γ-static fusimotor activity [56], and iii) postural muscle tone regulation [55]. Children also improved upper-thorax alignment; which could be critical to prevent vertebral pain and respiratory problems secondary to sustained spinopelvic and thoracic misalignments [57], [58]. Active control is a dimension assessed by numerous clinical tests. It requires high-level online sensorimotor control to coordinate active head movements while stabilizing the upper body [23], [59]–[62]. After TruST-intervention, children acquired the ability to perform head rotations with reduced compensatory trunk displacements and less motor variability during independent sitting. Perhaps, this sensorimotor improvement could be explained by the acquisition of coordinated proprioceptive- and vestibular-mediated neck-trunk neuromuscular responses that are under vestibulospinal, vestibulocolic, cervicospinal, and cervicooccipital reflexive control [63]–[65]. In regards to proactive control, children acquired shorter, straighter, and less variable reaching paths associated with proficient task-dependent postural strategies while sitting independently [32], [66]. Our two studies suggest that some children can improve both arm and seated postural control; while others maximize reaching distance by increasing trunk excursions as a plausible compensatory postural strategy to overcome the lack of elbow extension due to muscle paresis and/or spasticity [67], [68]. Collectively, the static, active, and proactive postural control improvements within the scope of our biomechanical analysis (inter-segmental head, upper-thorax, and lower-thorax angles, and pelvis with respect to space) may suggest that TruST-intervention can improve the disrupted internal sensory models that optimize balance and orientation while planning and executing goal-oriented tasks [63], [69], [70].

In summary, the present proof-of-concept study shows the tolerance, feasibility, and potential capability of TruST-intervention to promote functional and independent sitting in children with CP, GMFCS III-IV, and segmental trunk control impairments. TruST-intervention seems to be effective to maximize trunk and reaching control abilities in children with CP and postural sitting control limitations.

We should note that the therapeutic regimes of children were not discontinued; which could have potentially facilitated the maintenance of the improvements during the 3mos-washout period. Moreover, a larger sample size would be necessary to test the generalization of the observed postural and reaching control benefits to a CP population of similar clinical features and functional abilities. Furthermore, randomized clinical trials are granted to address superiority of TruST-intervention over matched-dose control therapies.

APPENDIX

Appendix I shows further details on i) children’s clinical features, ii) TruST-intervention motor learning-control principles, and iii) statistical procedures. In addition, 5 supplementary videos are included to display the TruST platform and some of the improved motor outcomes.

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A. M. Gordon et al., “Bimanual Training and Constraint-Induced


