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Rehabilitation of Postural Control and Gait in Children with Cerebral Palsy: the Beneficial Effects of Trunk-Focused Postural Activities

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ABSTRACT

Purpose: In children with cerebral palsy (CP), with impaired trunk control and toe-walking, trunk-focused rehabilitation (TFR) based on postural activities was hypothesized to improve trunk postural control, early trunk deceleration, and ankle dorsiflexion braking during walking. Methods: Seventeen children with CP (5–12 years) walking autonomously were randomly assigned to TFR and then usual rehabilitation (TFR-UR) or vice versa (UR-TFR).

Results: Only after TFR was significant improvements in (i) the Trunk Control Measurement Scale score, postural sway on an unstable sitting device and standing, and (ii) early sternal and sacral decelerations and coupled negative ankle power due to plantar flexors.

Conclusion: TFR improves trunk dynamics and consequently improves coupled toe-walking.

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cerebral palsy; child rehabilitation; gait analysis; trunk control; toe-walking

Introduction

Cerebral palsy (CP) describes a group of permanent, activity-limiting motor and posture disorders caused by lesions to the developing brain *in utero* or *post-partum*. The subsequent reorganization of central nervous system functions in children with CP also results in motor disorders. [1] Postural control disorders have a central place in motor deficits in children with CP and have been extensively studied in the literature.[2,3] Among the different body segments, upper body and especially trunk control is a key feature for an efficient postural control. Its stabilization allows the effective movements of the head and the distal segments,[4–7] the development of goal-directed activities and gross motor skills, and ensures the emergence of communicative and social skills by orienting the body and the head in an optimal way in the environment.[8,9] In addition, the postural control of the trunk, which accounts for about 60% of body mass in children,[10] is a key factor in the acquisition of locomotor balance.[4,11] Segmental trunk control, a typical development that occurs gradually throughout childhood,[12] is closely linked to gross motor performance in young infants[13] and is significantly delayed in preterm infants.[14,15] From early childhood onwards, children with CP display axial control disorders and abnormal postural control in the sitting position.[16,17] It has been recently shown that children with CP have specific impairments in trunk control during a self-stabilization task on an unstable sitting device compared to typically developing (TD) children.[18] These impairments in axial postural control (and particularly in trunk control) remain present throughout the motor development period – even after the child can stand and walk independently.[19,20] These deficits are of particular interest when one considers that trunk control deficits are strongly related to functional and gross motor function deficits in children with CP.[21–26]

The importance of the trunk during independent walking deserves attention given its potential role in the gait deviations seen in children with CP. However, despite a growing interest in trunk control in children with CP, the literature primarily reports evaluations and the effect of trunk intervention in non-autonomously walking or non-walking children (GMFCS III-V).[17,27–30] During gait, children with CP show significant deviations in trunk kinematics and kinetics; the trunk ranges of motion in all three planes of space are much greater than in TD children.[16,31–35] These deviations are associated with poor dynamic balance control during gait,[36] as reflected by larger step width,[37] greater variability in step length,[38] greater acceleration of the head, thorax (upper trunk), lower back (L3 region), pelvis, and body center of mass (CoM) in all three planes over the whole gait cycle and greater instability of the lower back relative to TD children.[39–41] These deviations can be seen as a maturational disorder of locomotor balance control. Indeed, control of the relative movements of the upper body segments and their stabilization in relation to space is a marker of locomotor development.[11] During walking, the body can be divided into two functional units: the locomotor unit and the passenger unit (the upper body) and walking is efficient when the stabilization demands of the passenger are minimized.[42] In children with CP, with poor control of their upper body accelerations,[43] impaired control of axial segments during walking could account for gait disorders[44] and the high contribution of the trunk and head to the increased

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mechanical work produced during walking.[45] Because the trunk and the lower limbs interact biomechanically and reciprocally during gait, in children with CP, trunk deviations lead to lower limb deviations, and *vice versa*.[19,46] In particular, kinetic deviations of the trunk related to impaired trunk postural control may need to be compensated by kinetic deviations of the lower limbs for balance control.

One of the most common lower limb deviations encountered in children with CP is toe-walking. This is defined as the absence of the first (heel) rocker as the children first strike the ground with the foot flat or with the forefoot upon initial contact (IC).[42,47] Thus, IC is immediately followed by the second rocker, and the tibia rolls over the ankle.[42] At IC, the ankle angle is often in plantar flexion, i.e., equinus.[48] The absence of the first rocker in children with CP is also associated with early-onset intense power absorption and negative work exerted at the ankle joint,[49,50] which in turn decelerates ankle dorsiflexion and the anterior tilt of the tibia during the weight acceptance (WA) phase of gait (defined as the period of combined initial power absorption activity around the lower limb joints).[51] This behavior involves early-onset activity of the triceps surae, which starts at the terminal swing and lasts throughout the WA phase.[52] Prolonged plantar flexor activity during gait in children with CP is generally considered to be due to spasticity (hyper-excitable stretch reflexes) and to induce equinus.[1] Nevertheless, the existence and/or functional significance of exaggerated stretch reflexes during gait in spastic patients has been subject to debate for decades.[53–55] In particular, spasticity is unlikely to contribute to toe-walking in children with CP; soleus activity during the swing phase is depressed,[49,54] and an exaggerated reflex activity is absent.[56] In contrast, toe walking in both children with CP and TD children is characterized by feed-forward control of the ankle muscles – suggesting that this gait pattern is part of an adaptive process.[57]

When the second rocker begins, the plantar flexors decelerate the ankle dorsiflexion, slow the trunk's forward progression, and support the body by accelerating it upward.[42,58] This upward acceleration of the body can be accomplished by either moving the CoM upward or decelerating the CoM's downward movement.[59] In children with CP, plantar flexor activity associated with the early second rocker in WA results in negative ankle power, which decelerates the ankle dorsiflexion and thus decelerates the body's CoM in the downward and forward directions.[60] All of these actions contribute to the greater negative work exerted on the CoM by the lead leg in children with CP, relative to TD children.[50] The presence of the above-mentioned trunk control disorders and impaired dynamic balance control during gait in CP suggests that the early activation of plantar flexors and the strong negative ankle power during WA associated with toe-walking might correspond to an adaptive mechanism for decelerating the trunk's forward and downward displacements, in order to compensate for poor balance and poor postural control of the trunk.

Very few studies have focused on trunk control as a therapeutic target in the management of cerebral palsy.[28,61–63] Therefore, there should be a strong interest in studying the effects of a treatment targeting trunk control,[64] especially for gait and postural rehabilitation of children with CP who are able to walk independently. The objective of this study was to determine whether a trunk-focused rehabilitation (TFR) strategy based on postural activities would improve postural control of the trunk itself and the body during standing and walking in children with CP. We first hypothesized that participation in a TFR program, essentially based on balance control self-exercises involving the trunk, over a 3-month period would (i) improve postural control of the trunk (as evidenced by a higher score at trunk control measurement scale (TCMS), a clinical scale to measure trunk control, and less CoP sway during the unstable sitting postural task), (ii) reduce CoP sway during stance. During gait, we hypothesized that children with CP, compared to TD children would have a larger step width (due to impaired balance)[37] and greater peak of anterior deceleration of the sternum (upper trunk), downward deceleration of the sacrum (CoM) and negative ankle power during the WA phase. We hypothesized that TFR in children with CP would improve all these variables during gait, including peak negative ankle power. Indeed, we expect the peak sternum and sacrum decelerations to be correlated with the peak negative ankle power during WA, due to the plantar flexors' action on the trunk or CoM.[58,60]

Materials and Methods

Participants

Seventeen children with CP [mean (standard deviation (SD)) age: 7.9 (2.4) years; age range: 5–12 years; 8 girls] and 17 age-matched TD children [mean (SD) age: 7.7 (2) years; age range: 5–11 years; 7 girls] participated in the study. The main inclusion criteria for the children with CP were as follows: age between 5 and 12, the ability to walk without aids (Gross Motor Function Classification System level: I or II), little or no contracture of the triceps surae (defined as forced ankle dorsiflexion of at least 5° with the knee extended), and the presence of soleus spasticity, according to the Tardieu scale [angle $X = 17°$ (9); spasticity grade Y of 1 ($n = 10$) or 2 ($n = 7$)]. The main exclusion criteria were botulinum toxin injections in the lower limbs in the 6 months preceding the study, lower limb surgery in the 12 months preceding the study, any changes in physical or orthopedic therapy within the previous 2 months, hip flexion of more than 20°, and pain in the lower limbs when standing or walking. The TD children had to be able to walk independently at 18 months of age, with no history of neurological or orthopedic disease, no history of lower limb surgery, and no pain. Each child was required to have sufficient cognitive level and cooperation to perform the tasks (mimic movements involving the trunk for TCMS, stabilize alone in sitting and standing, walk as usual) and give verbal consent to participate in the experiment. The parents also gave their written, informed consent to their child's participation in the study. The experimental protocol complied with the tenets of the Declaration of Helsinki and was approved by the local investigational review board (*Comité de Protection des Personnes Est-III*, Nancy, France; reference: 2015-A000022-47/15.02.03). This clinical trial was registered at ClinicalTrials.gov (reference: NCT04287673).

Table 1. Characteristics of the study populations, by subgroups.

	Children with CP TFR – UR (*n* = 8)	Children with CP UR – TFR (*n* = 9)	TD children (*n* = 17)
GMFCS level I/II	3/5	6/3	/
Hemiplegic/diplegic	3/5	3/6	/
Age (years)	9 (2.5)	7.6 (2.3)	7.7 (2)
Height (cm)	133 (14)	124 (15)	128 (14)
Weight (kg)	29.5 (6.1)	28 (13.7)	25.6 (6.8)

Data are quoted as the mean (SD). CP: cerebral palsy; TD: typically developing; TFR: trunk-focused rehabilitation; UR: usual rehabilitation; GMFCS: Gross Motor Function Classification System.

All the children with CP were randomly assigned in a balanced manner by a custom algorithm on Matlab® to one of the two rehabilitation programs: 3 months of TFR and then 3 months of the child's usual rehabilitation (UR), or 3 months of UR and then 3 months of TFR. The study participants' characteristics and the group assignments are summarized in Table 1. CP and TD groups are equivalent (mean and standard deviation) in terms of age, height, and weight.

Study Design

We performed a prospective, randomized, two-arm, single-center study over a 6-month period (Figure 1). Children with CP performed TFR or UR for 3 months and then switched to the other rehabilitation phase for the next 3 months. They were evaluated before the start of the rehabilitation program (at M0), within a week of the end of the first phase (at M3), and within a week of the end of the second phase (at M6). Since the usual care protocol for all children with CP included usual physiotherapy care, it was not possible to include a washout period at M3. The TD children were evaluated one time (M0). The evaluations (the TCMS, the unstable sitting task, the standing postural task, and a three-dimensional (3D) clinical gait analysis) were not performed in the same order for all children. The children always rested for the same amount of time between each task.

Evaluations

The Trunk Control Measurement Scale

TCMS (developed by Heyrman et al.)[65] provides a clinical and functional evaluation of the trunk. The child (sitting on the edge of a table) is asked to actively move his/her arms and legs (with the trunk stabilized) and then other body segments (including the trunk). Each item is performed three times, and the best performance is considered for scoring. The maximum possible (best) score is 58, and the lowest possible (worst) score is 0.

The Unstable Sitting Postural Task

The subject sat on an unstable seat device (Figure 2) placed on a 3D force platform (AMTI, Watertown, MA, USA). The seat was able to tilt in a frictionless manner, thanks to a cardan joint and four springs arranged around the latter. Seat movements were only possible along the mediolateral and anteroposterior axes (maximum tilt: 12°). During an initial calibration, the distance between the springs and the cardan joint (placed at the pivot point) was adjusted, to graduate the instability of the seat and make the difficulty of the postural task independent of

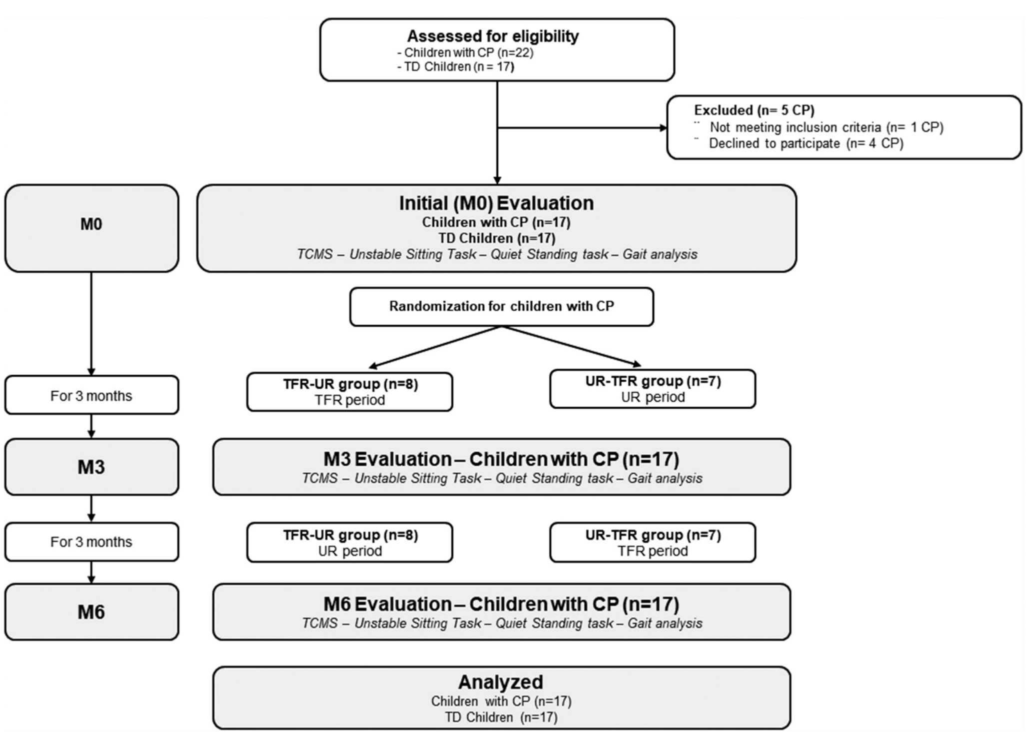

Figure 1. Flow chart and study design. Children with cerebral palsy (CP) were randomly allocated to Trunk-Focused Rehabilitation (TFR) for three months and then Usual Rehabilitation (UR) for three months (forming the TFR-UR group), or vice versa (forming the UR-TFR group). The children with CP were evaluated before the start of the rehabilitation program (at M0), within a week of the end of the first phase (at M3), and within a week of the end of the second phase (at M6). The typically developing (TD) children were evaluated one time (M0).

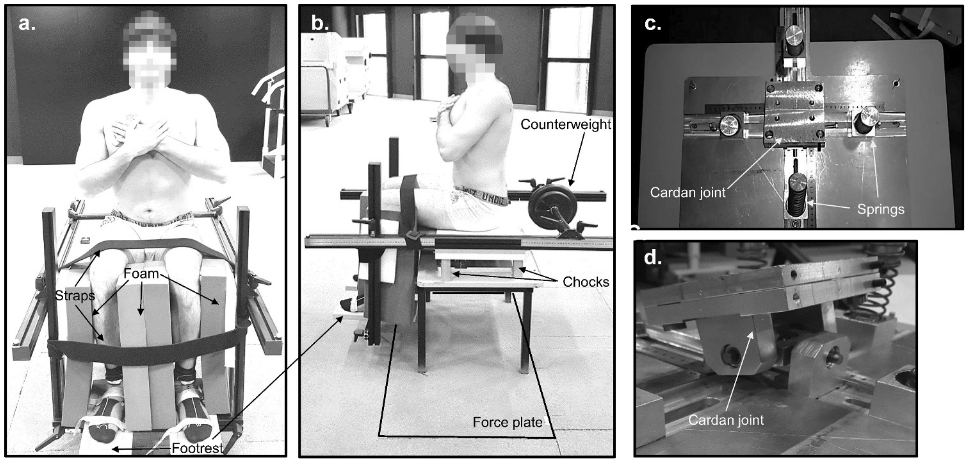

Figure 2. The unstable seated device and the tilt mechanisms. Frontal (A) and sagittal (B) views of the set-up used in the unstable sitting postural task. When chocks were removed, the participant stabilized himself in an upright upper body posture. Body movements and device movements were solely controlled by the child's head and trunk position. Note that only children participated in this study and that an adult is depicted on these pictures for publication purpose. (C) Underside and (D) three-quarter views of the tilt mechanisms of the device, showing the cardan joint and the four springs.

the participant's anthropometric characteristics. The subject's position on the seat was standardized, with the arms crossed on the chest, and the hips, knees, and ankles held in flexion at an angle of 90°. Lower limb movements were restricted; hence, body movements and device movements were solely controlled by the child's head and trunk position.[12,18] The subject was instructed to remain as still as possible for 30 s in an upright position.

The Quiet Standing Postural Task

The subject stood upright on a 3D force platform with the arms alongside the body and the feet a hip width apart. He/she was instructed to stand as still as possible for 30 s.

For both the standing and unstable sitting postural tasks, three trials were carried out with the eyes open. Between each trial, the participant could rest for at least 30 s. The CoP trajectory was recorded at a sampling rate of 1000 Hz. The raw data were filtered with a low-pass Butterworth filter (order 4; cutoff 12 Hz). Using these data, we calculated the average values (over three trials) for the CoP area (in mm,[2] computed from the 95% confidence ellipse of the CoP displacement), and the CoP mean velocity ($mm.s^{-1}$).

Three-Dimensional Gait Analysis

A 3D optoelectronic motion capture system (Vicon Motion Systems Ltd, Oxford, UK) was used to record kinematic gait data. The cameras were sampled at 100 Hz. Reflective markers were placed on the subject's skin according to the conventional gait model[66] in which a simplified "trunk" is considered to have two modules: the thorax (part of the upper trunk) and the pelvis (part of the lower trunk). The participants were asked to walk several times at a self-selected speed along a 12 m track with embedded force platforms (AMTI, Watertown, MA, USA). Kinetic data were sampled at 1000 Hz and synchronized with the kinematic data.

The data were processed using Vicon Nexus software (version 1.8.5), Vicon Polygon software (version 3.5.2; both from Vicon Motion Systems Ltd), and MATLAB R2017 software (MathWorks, Inc., Natick, MA, USA). The following time-distance variables were calculated: dimensionless walking speed (=walking speed (in $m.s^{-1}$)/$\sqrt{g.LL}$, where g, acceleration of gravity (=9.81 $m.s^{-2}$) and LL, leg length (m)) and dimensionless step length (=step length/LL) (see Hof, 1996),[67] and dimensionless step width (=step width/pelvic width). Ankle dorsiflexion (in degrees, °) was measured at IC, with the ankle angle defined as the foot-tibia angle.[68] During the WA phase, we measured the amplitude of the peak negative ankle power (in watts per kg, $W.kg^{-1}$), the amplitude of the peak anterior deceleration of the sternum and the amplitude of the peak downward deceleration of the sacrum (in $m.s^{-2}$). We considered the anterior deceleration of the sternum as a proxy for the plantar flexors' braking effect on the upper trunk's forward progression.[58,60] We considered the peak downward deceleration of the sacrum as a proxy for the plantar flexors' gravity-resisting effect on the CoM,[58,60] given the excellent correlation between the vertical acceleration of this marker and the vertical acceleration of the CoM.[69] It should be noted that we chose to use the term "downward deceleration" rather than "upward acceleration," in order to emphasize that the sacrum's downward movement slows during the WA phase.[42,59] All the gait data reported below were averaged over five gait cycles.

Rehabilitation Procedures

Each child with CP participated in two physiotherapy sessions per week for a total of 6 months (3 months of UR followed by 3 months of TFR, or *vice versa*) under the direction of the private physiotherapist caring for them. All the physiotherapists contacted agreed to participate in the study. They were initially briefed on the principles of TFR and given detailed instructions on its content shortly before the start of the TFR treatment period. Each session lasted 45–60 minutes and the child was given exercises to perform daily at home for 10–30 minutes depending on the parents' availability. The UR corresponded to the type of

Figure 3. Examples of postural activities included in the Trunk-Focused Rehabilitation. The child (with left hemiplegia, in this example) hit a target with one leg while bridging (left) or pushed with her right arm to spin herself around on an unstable support (Domyos® Abdo Gain Trainer, Decathlon SA, Villeneuve d'Ascq, France) (right). In both postural activities, the trunk was strongly involved in postural control, and the child controlled her balance without assistance from the therapist.

rehabilitation already received by the child before the study; it variously combined muscle stretching, muscle strengthening (e.g., resistance training), muscle tone reduction (e.g., Bobath concept neuro-developmental treatment), and upper and lower limb motor skill training facilitated by the therapist. These therapies, involving limited groups of muscles in elementary stretching or actions, targeted the lower limb muscles in all cases, the upper limb muscles in some cases, and the trunk muscles only in two cases. The therapist often supported the child and helped him/her to control his/her balance. The TFR program was not based on strengthening the elementary muscles of the trunk, but on improving postural control and balance of the whole body, including the trunk and other affected muscles, by means of postural activities performed autonomously by the patient in intermediate postures involving the trunk. Thus, the principle of this approach was, during autonomous actions in intermediate postures, to exploit the fundamental automatic control of postural support and balance to improve the use of affected muscles in support and balance not only during these actions but also during all postural and locomotor tasks, an original approach proposed for the rehabilitation of stroke patients.[70] The child had to control his or her balance during various voluntary actions, starting from intermediate postures, such as being on all fours, bridging, or sitting on an unstable support (see Figure 3). These autonomous actions were less challenging than standing and walking but were expected to have beneficial effects on the latter. Starting from intermediate postures, the child also performed challenging trunk movements, requiring the dissociation of scapular and pelvic girdle movements or a reduction in lumbar lordosis. The pre-study upper and lower limb rehabilitation goals given in the UR phase (e.g., hamstring stretches, plantar flexor stretches, and wrist extensions) were included in some of the exercises in the TFR phase. For example, from an all-fours position, the child had to fully extend the knees to get hamstring and plantar flexor stretches. Finally, each child was given a selection of TFR postural activities to perform at home daily.

Statistical Analysis

Quantitative data were reported as the mean (SD). A two-sample t-test was used to compare children with CP at M0 and TD children for each gait variable (see Pierret et al. 2021[18] for TCMS and the postural tasks). In children with CP, correlation tests were performed using Pearson's coefficient to test the correlations between kinetic variables during walking. We also performed mixed-design analyses of variance with "group" (TFR-UR, UR-TFR) as the between-participant factor and the "evaluation time" (M0, M3, and M6) as the within-participant factor. While the interaction between "group" and "evaluation time" was statistically significant for a given variable, size effects were reported for the partial eta 2 ($\eta_p 2$), and the Newman–Keuls post-hoc test was used to compare the values recorded at the different evaluation times (M0, M3, and M6) for each group. The threshold for statistical significance was set to $\alpha = 0.05$. All statistical analyses were performed using Statistica software (version 13, Tibco Software Inc., Palo Alto, CA, USA).

Results

Effects of TFR and UR on Postural Control of the Trunk in Children with CP

The Trunk Control Measurement Scale

In the TFR-UR group, the TCMS score was significantly higher at M3 and M6 than at M0; the difference between M3 and M6 was not significant. In the UR-TFR group, the TCMS score was significantly higher at M6 than at M0 and M3; the difference between M0 and M3 was not significant (Table 2). In addition, the post-hoc test for the group × intervention time interaction showed that TCMS was significantly better at M3 for the TFR-

Table 2. TCMS scores, postural variables, and gait variables in the two groups of children with cerebral palsy (TFR-UR and UR-TFR groups) at M0, M3, and M6.

	TFR-UR group			UR-TFR group			group*evaluation time interaction (ANOVA)		
Trunk Control Measurement Scale	M0	M3 (post-TFR)	M6 (post-UR)	M0	M3 (post-UR)	M6 (post-TFR)	$F_{(2.30)}$ *value*	*p* value	η_p^2
Total score	35 (9)	47 (7)**	44 (5)**	37 (4)	38 (4)	47 (4)** ††	22.4	**<0.001**	0.60
Unstable sitting postural task									
CoP area (mm^2	3383 (870)	2816 (907)**	2997 (953)** †	3239 (777)	3182 (671)	2628 (787)** ††	$F_{(2,28)}$ = 30.5	**<0.001**	0.69
CoP velocity (mm.s^{-1})	47 (10)	32 (9)**	43 (10) ††	45.3 (11)	47 (11)	36 (9) ** ††	26.7	**<0.001**	0.66
Quiet standing postural task									
CoP area (mm^2	1020 (402)	751 (325) **	948 (346) ††	1074 (289)	1110 (280)	780 (263) ** ††	41.4	**<0.001**	0.73
CoP velocity (mm.s^{-1})	17 (4)	14 (2) **	16 (4) †	17 (3)	18 (2)	14 (3) ** ††	16.0	**<0.001**	0.51
Gait analysis									
Time-distance variables									
Walking speed (dimensionless)	0.41 (0.06)	0.46 (0.04)	0.42 (0.04)	0.43 (0.06)	0.40 (0.06)	0.45 (0.09) †	7.2	**0.002**	0.32
Step length (dimensionless)	0.85 (0.32)	0.90 (0.37)	0.83 (0.32)	0.79 (0.09)	0.77 (0.11)	0.84 (0.14) †	7.4	**0.002**	0.33
Step width (dimensionless)	0.77 (0.20)	0.58 (0.16)	0.63 (0.18)	0.72 (0.24)	0.82 (0.29)	0.62 (0.33) †	5.7	**0.004**	0.28
Kinematic and kinetic variables									
Dorsiflexion at IC (°)	−8 (8)	−6 (7)	−10 (9)	−2 (9)	−3 (11)	−3 (9)	1.6	0.226	
WA peak ankle power (W.kg^{-1})	1.49 (0.75)	0.85 (0.26) **	1.31 (0.39) †	1.66 (0.74)	1.56 (0.65)	0.94 (0.30) ** ††	9.3	**<0.001**	0.38
WA peak sternum anterior deceleration (m.s^{-2})	3.2 (1.3)	2.1 (0.7) **	2.6 (0.8)	2.9 (0.8)	3.1 (0.8)	2.2 (0.7) * ††	8.9	**<0.001**	0.37
WA peak sacrum downward deceleration (m.s^{-2})	6.0 (2.5)	4.4 (2.8) **	5.5 (1.3) **	10.2 (3.3)	9.2 (3.8)	5.4 (2.6) ** ††	5.7	**0.007**	0.27

Values are quoted as the mean (SD). TFR: trunk focused rehabilitation; UR: usual rehabilitation; ANOVA: analysis of variance; CoP: center of pressure; IC: initial contact; WA: weight acceptance; * p < .05, ** *p* <.01 M3 or M6 vs. M0 in the same group, † p < .05, †† p < .01 M6 vs. M3 in the same group. Note a clear trend (p = .051) toward a lower step width at M3 than at M0 in the TFR-UR group.

UR group compared to the UR-TFR group ((47(7.3)) vs. 38.1 (5.5), $p = .02$), whereas it was not significantly different at M0 (35(9) vs. 37(4), $p = .41$).

The Unstable Sitting Postural Task

In the TFR-UR group, both the CoP area and the CoP velocity were significantly lower at M3 than at M0, and M6 and the CoP area was maintained significantly lower at M6 than at M0 (Table 2). In the UR-TFR group, neither the CoP area nor the CoP velocity differed significantly when comparing M0 and M3, and both were significantly lower at M6 than at M0 and M3.

Correlation Between TCMS and Postural Variables in Unstable Sitting Task

In children with CP, TCMS was significantly correlated with the CoP velocity at the three evaluation time point (M0: $r = -0.50$, $p < .05$; M3: $r = -0.75$, $p < .001$; M6: $r = -0.71$, $p < .001$) and also with the CoP Sway Area (M0: $r = -0.68$, $p < .01$; M3: $r = -0.60$, $p < .05$; M6 $r = -0.70$, $p < .01$).

Effects of TFR and UR on the Quiet Standing Postural Task in Children with CP

In the TFR-UR group, both the CoP area and the CoP velocity were significantly lower at M3 than at M0 and at M6 (Table 2). In the UR-TFR group, neither the CoP area nor the CoP velocity differed significantly when comparing M0 and M3, and both were significantly lower at M6 than at M0 and M3.

Gait in Children with CP and TD Children at M0

The CP and TD groups differed significantly regarding all variables except step length (Table 3). Children with CP

Table 3. Gait variables in children with CP at M0 and in TD children.

	TD group (*n* = 17)	CP group (*n* = 17)	*t-test values (df = 32)*	*p values*
Time-distance variables				
Walking speed (dimensionless)	0.46 (0.05)	0.40 (0.06)	2.45	0.019
Step length (dimensionless)	0.87 (0.06)	0.81 (0.22)	0.98	0.331
Step width (dimensionless)	0.59 (0.09)	0.75 (0.22)	2.73	0.010
Kinematic and kinetic variables				
Dorsiflexion at IC (°)	1 (3)	−5 (9)	2.44	0.020
WA peak ankle power (W.kg^{-1})	0.3 (0.1)	1.6 (0.7)	7.43	<0.001
WA peak sternum anterior deceleration (m.s^{-2})	1.1 (0.3)	3.0 (1.1)	22.48	<0.001
WA peak sacrum downward deceleration (m.s^{-2})	3.1 (1.1)	9.4 (3.4)	14.27	<0.001

Values are quoted as the mean (SD). CP: cerebral palsy; TD: typical developing; IC: initial contact; WA: weight acceptance; df: degrees of freedom.

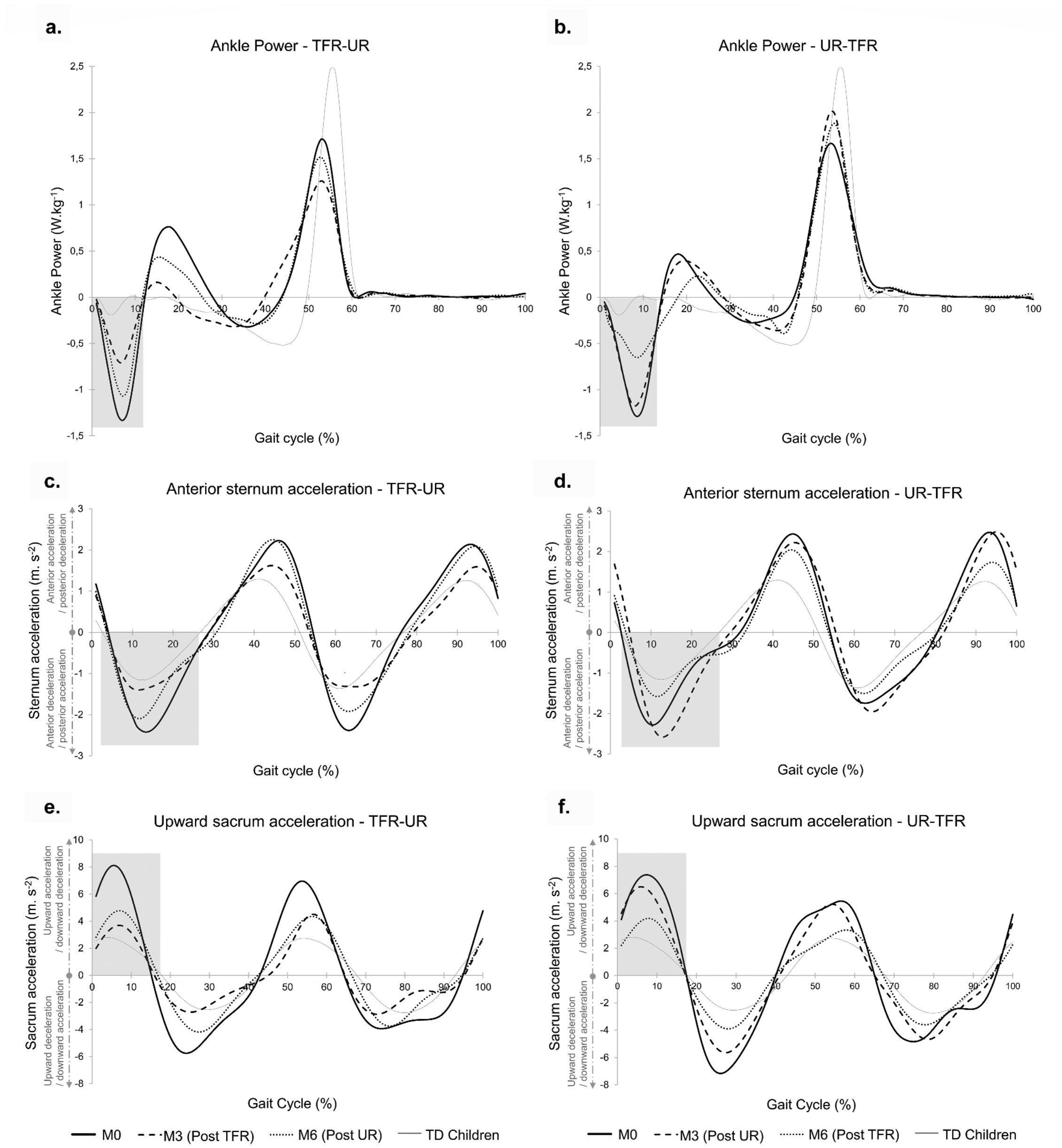

Figure 4. Mean ankle total power (A,B), mean anteroposterior acceleration of the sternum marker (C,D), and mean upward acceleration (i.e. downward deceleration) of the sacrum marker (E,F), during gait, in children with cerebral palsy (CP) who performed TFR and then UR (A, C, E, n=8) or UR and then TFR (B, D, F, n=9), and in TD children (all panels, n=17). TFR: trunk-focused rehabilitation; UR: usual rehabilitation; TD: typically developing. Black lines correspond to the CP group (solid line for M0, dashed line for M3 and dotted line for M6) and the solid grey line corresponds to the TD group at M0. The rectangle corresponds to the area of interest for the peak during the weight acceptance phase. Significant differences are summarized in Table 3.

walked significantly more slowly and took wider steps than the TD children. The mean ankle angle at the time of IC was plantar flexion in children with CP and slight dorsiflexion in children with TD. During WA, the peak sternum anterior deceleration, the peak sacrum downward deceleration, and the peak negative ankle power were all significantly higher in children with CP than in TD children (Table 3, Figure 4).

Effects of TFR and UR on Gait in the Children with CP

The time-distance variables in the TFR-UR group did not differ significantly at the different evaluation times, although we observed a clear trend ($p = .051$) toward a lower step width at M3 than at M0 (Table 2). In the UR-TFR group, the step width was significantly lower at M6 than at M3, and both the walking speed and step length were significantly higher at M6 than at M3. For ankle dorsiflexion at IC, the interaction between the "group" and "evaluation time" factors was not statistically significant. For kinetic variables in the TFR-UR group, the peak negative ankle power (Figure 4A), the peak sternum anterior deceleration (Figure 4C), and the peak sacrum downward deceleration (Figure 4E) were significantly lower at M3 than at M0 (Table 2). At M6 compared to M0, only the peak sacrum downward deceleration remained significantly lower. At M6 compared to M3, only the peak negative ankle power was significantly different (higher value). In the UR-TFR group, the peak negative ankle power (Figure 4B), the peak sternum anterior deceleration (Figure 4D), and the peak sacrum downward deceleration (Figure 4F) were significantly lower at M6 than at M0 and M3 (Table 2).

Correlation Between Ankle and Trunk Kinetic Variables During Gait

In the children with CP, during WA, the peak negative ankle power was significantly correlated with the peak sternum anterior deceleration at all three evaluation time points (M0: $r = 0.68$, $p = .02$; M3: $r = 0.55$, $p = .02$; and M6: $r = 0.53$ $p = .02$) and with the peak sacrum downward deceleration at the first two time points (M0: $r = 0.63$, $p < .01$; M3, $r = 0.52$ $p = .03$ and M6, $r = 0.34$ $p = .18$). In the TD children, the peak negative ankle power was not significantly correlated with the peak sternum and sacrum deceleration ($r = -0.18$ and -0.03, respectively).

Discussion

This study has shown that a 3-month TFR program but not a UR program was associated with (i) better postural control of the trunk (assessed with TCMS and unstable sitting postural task), (ii) more stable quiet standing posture, and (iii) lower sternum anterior deceleration, sacrum downward deceleration, and negative ankle power during the WA phase of gait. Furthermore, a correlation between upper body dynamics and mechanical braking at the ankle joint was shown in children with CP. Indeed, during the WA phase of gait, we observed a powerful braking of ankle dorsiflexion (i.e., peak negative ankle power, not observed in the TD group) which was correlated with the sternum anterior deceleration at all three evaluation time points and the sacrum downward deceleration at two evaluation time points.

Beneficial Effects of the Trunk-Focused Rehabilitation on Trunk Postural Control and Standing Control

This study is the first randomized crossover trial to assess the effect of trunk targeted rehabilitation on trunk control and standing postural control in children with cerebral palsy who are able to sit, stand, and walk independently. Indeed, previous studies involving trunk targeted intervention have assessed its effects on gross motor function rather than trunk control specifically[71,72] or in more severely affected children (GMFCS III-V).[28,63 27,73] on trunk control, the Trunk Impairment Scale,[74] a trunk assessment tool developed for post-stroke adults, has been used but is not suitable for assessing trunk control asymmetries in children with CP.

In both subgroups of children with CP, the TFR phase was associated with a significant improvement in postural control of (*i*) the trunk (according to TCMS and performance in the unstable sitting task) and (*ii*) the body during quiet standing. Although TCMS was assessed by a single rater who was not blinded to group assignment, this potential methodological bias probably had little or no impact on rehabilitation effects because TCMS was strongly and significantly correlated with objective postural variables in the unstable sitting task at all evaluation time points. Thanks to the quasi-crossover design study (without a washout period since it was impossible to deprive the patients of their usual physiotherapy between the two rehabilitation periods), we can assume that these improvements are specifically due to TFR and not only a general effect of any rehabilitation. Indeed, the improvements observed post-TFR at M3 in the unstable sitting and the quiet standing postural tasks faded (to a lesser extent for CoP area parameter during the unstable sitting task) after UR was measured at M6. In the same way, TCMS scores increased post-TFR at M3 but were only kept at a comparable level after UR, at M6. However, in the UR-TFR group that began with UR, improvements on the different parameters appeared only at M6 after the TFR, and not at M3 after the UR.

It is suggested that the remarkable effects of TFR are primarily due to the exploitation of subcortical automatic control of support and balance through selected independent actions in intermediate postures, such as the trunk and other affected muscles, which would further contribute to the postural control of support and balance, according to a new rehabilitation approach.[70] The TFR program also follows nonspecific motor learning principles known to be effective in the management of children with CP: goal-directed movements and repetition of exercises of increasing difficulty.[63,75–77] Initially, safe postures for balance, followed by balance control exercises of progressively increasing difficulty, would promote long-term functional benefits through neural plasticity.[63,78,79] In particular, anticipatory postural mechanisms for support and balance are automatically involved in self-exercises, for example, when the child has to stabilize on an unstable support (right image in Figure 3) that is destabilized by upper body movements. Postural control in this case relies on anticipatory control with feedforward mechanisms[12] that are related to internal models of action and body schema.[80,81] Thus, this balance training, combined with postural activities involving high coordination between the head, trunk, and distal segments, could improve the internal models of action that may be disturbed in children with CP, and thus improve the children's balance but also their functional abilities.[63] Similarly, the good correlation between TCMS and the CoP sway parameters during the unstable sitting task suggests that trunk functional control is related to trunk balance abilities.

Trunk Control Impairment During Gait in Children with CP

Previous studies have shown that children with CP have deficits in trunk postural control.[18,65] These impairments are known to be strongly linked with impairments in gross motor function[23] but also with impaired postural control during standing.[18,82] During gait, children with CP show significantly greater acceleration of the sternum, lower back (L3 region) and sacrum throughout the whole gait cycle, when compared with TD children.[40] In the present study, we specifically observed greater peak sternum anterior deceleration and greater peak sacrum downward deceleration during the WA phase of gait. The latter finding is in line with the very high downward deceleration of the CoM that is known to occur during the first double support phase in children with CP.[39] Our observations for the WA phase are important for gait kinetics because they indicate a greater restraint of the forward momentum of the body and the fall of the CoM – both of which challenge balance control. The larger step width broadens the support base during the double support phase, and highlights the balance difficulties encountered by children with CP during gait.[36,37,83]

Beneficial Effects of the Trunk-Focused Rehabilitation on Gait

Since the postural control of the trunk is crucial for balance control during walking,[4,84] we suggest that the observed improvement in motor behavior was primarily due to the TFR's beneficial effect on the postural control of the trunk. Indeed, a decrease in both peak sternum anterior deceleration and peak sacrum downward deceleration during the WA phase of gait is observed in both groups after the TFR phase. Combined with the reduction in step width, this improvement in trunk dynamics suggests better control of axial segments during walking and a better locomotor balance.

In fact, the TFR included postural activities (such as being on all fours, bridging, or sitting on an unstable support (Figure 3)) during which the trunk was strongly involved in various actions and in balance control. Even though the rehabilitation program implemented in the present study did not include specific locomotion training, there was still an improvement in walking, as indicated by a shorter step width during walking and a reduction in trunk and CoM deceleration during the WA phase of gait. We hypothesize that the improved balance during gait results from a greater contribution of the trunk to dynamic balance control. Accordingly, the balance strategy observed before TFR (involving high trunk deceleration and negative ankle power at WA) was less evident after TFR.

Other rehabilitation protocols such as hippotherapy have shown potential benefits in postural control and gait in children with CP[62,85–88] but the results are inconsistent. It is hypothesized that the horse's movement stimulates the pelvis to reproduce its movements during walking, stimulating the vestibular system and proprioception, activating the trunk muscles, and leading to improved control.[86,89] While beneficial effects are observed on walking and balance in CP children, a recent review concludes that hippotherapy is not superior to conventional physical therapy in improving gross motor function, trunk control, or gait function.[90] However, hippotherapy involves the child and his or her trunk in a relatively passive manner, which, like passive neurodevelopmental therapy, may not be sufficient to improve motor functions.[76] On the contrary, in the TFR program, through postural activities in intermediate postures involving more or less all four limbs for body support and balance, the trunk is strongly and automatically involved in the control of support and balance. The consequent improvement in postural control of the trunk would then be beneficial not only for postural control in sitting but also for motor control during whole-body movements and/or walking.

Unfortunately, we did not assess gross motor function before and after the TFR and UR phases in children with CP. However, the children's parents anecdotally reported various functional improvements after the TFR phase, such as fewer falls, a better sitting posture, greater walking endurance, or the ability to perform new motor activities (e.g., cycling).

Medium Term Outcome of Trunk-Focused Rehabilitation

Our results show that, in the TFR-UR group, the benefits of TFR were only partially maintained 3 months after the end of this rehabilitation: significant improvement compared to M0 was maintained for trunk control, as reflected by the TCMS score and the CoP area in the unstable sitting task, and for peak sacrum downward deceleration during WA of gait. This persistence of motor effect could be related to a greater inclusion of trunk involvement in the automatic postural control of support and balance by the fact that the child had to manage his or her own support and balance in the TFR program postural activities. It would be interesting to increase the duration of TFR by including postural activities of this program in the child's everyday activities. To facilitate gait analysis, the present study included children aged 5 and over. Trunk-focused rehabilitation in even younger children is expected to have comparable or greater motor effects given the important development of postural control in young children and warrants investigation in the future.

Are Ankle and Trunk Kinetics Coupled During WA in Children with CP?

In our analysis of the WA phase of gait in children with CP, we observed moderate-to-strong correlations between the peak negative ankle power, on one hand, and the peak sternum anterior deceleration at M0, M3, and M6 and peak sacrum downward deceleration at M0 and M3 on the other. This correlation is in line with the early action exerted by the plantar flexors, since the angular deceleration of the trunk in the sagittal plane is strongly and primarily influenced by the plantar flexion moment generated at the ankle at the beginning of the stance phase.[91] In toe-walking, the plantar flexors exert a decelerating action on ankle dorsiflexion, the associated anterior tilt of the tibia,[92] and the downward and forward displacements of the CoM and the trunk from IC onwards.[58,60]

The plantar flexors' early activity at the end of the swing phase and during WA in toe walking has been attributed to spasticity as a primary impairment.[1,93,94] However, this hypothesis has been questioned in other studies of gait in children with CP.[53,54] In particular, spasticity is unlikely to contribute to toe-walking in children with CP because (i) the soleus activity during the swing phase is as low as normal,[12,54] and (ii) exaggerated reflex activity is not observed.[56] In contrast, the deceleration of ankle dorsiflexion by plantar flexors during WA in children with CP might have a functional role in gait. This hypothesis is supported by a study of children with

CP walking with negative-heel shoes and barefoot.[49] Although a kinematic adaptation to the shoes occurred upon IC (consisting of ankle dorsiflexion when the children wore negative-heel shoes and equinus when the children walked barefoot), toe walking was maintained and an equivalent deceleration of ankle dorsiflexion by the plantar flexors was observed in the two footwear conditions.[49] It is noteworthy that during the WA phase, the plantar flexors' direct effect on deceleration of the anterior tilt of the tibia and their indirect effect on the forward and downward displacement of the trunk occur in children with CP but not in TD children. In other words, toe-walking enables the plantar flexors to contribute substantially to the negative work exerted by the leading leg joints during the WA phase.[51] These actions might prevent joint collapse, provide vertical support,[59] decelerate the body's CoM, and change the direction of the CoM's velocity vector.[95]

At M6, the lack of a significant correlation between negative ankle power and sacrum downward deceleration might be due to a lower contribution of the plantar flexors to deceleration of the downward displacement of the sacrum (or the CoM) and thus better trunk control in the TFR-UR and UR-TFR groups. However, advanced biomechanical analyses[58,91] would be needed to study the contribution of the plantar flexors to the sagittal acceleration of the CoM or trunk in children with CP.

Conclusion

In children with CP with impaired trunk control and toe-walking, TFR, but not UR, significantly improved (i) TCMS, postural sway on an unstable sitting device and during standing, and (ii) early sternal and sacral decelerations and early coupled negative ankle power during waking. TFR is an original approach that exploits, during autonomous postural activities in intermediate postures strongly involving the trunk, the automatic postural control of support and balance for a better involvement of the affected muscles during these actions but also during all postural and locomotor tasks. This study highlights the importance of the impairment of trunk postural control in the impaired dynamic control of sitting, standing, and walking. The improvement by TFR in negative ankle power and coupled trunk decelerations during WA suggests that the early negative ankle power exerted by the plantar flexors in toe walking contributes to compensate for the impaired trunk control.

List of Abbreviations

CoM	Center of mass
CoP	Center of pressure
CP	Cerebral palsy
IC	Initial contact
SD	Standard deviation
TCMS	Trunk control measurement scale
TD	Typically developing
TFR	Trunk-focused rehabilitation
UR	Usual rehabilitation
WA	Weight acceptance

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