The use of turning tasks in clinical gait analysis for children with cerebral palsy

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Abstract

Background: Turning while walking is a crucial component of locomotion that is performed using an outside (step) or inside (spin) limb strategy. The aims of this paper were to determine how children with cerebral palsy perform turning maneuvers and if specific kinematic and kinetic adaptations occur compared to their typically developing peers.

Methods: Motion capture data from twenty-two children with cerebral palsy and fifty-four typically developing children were collected during straight and 90° turning gait trials. Experimental data were used to compute spatio-temporal parameters, margin of stability, ground reaction force impulse, as well as joint kinematics and kinetics.

Findings: Both child groups preferred turning using the spin strategy. The group of children with cerebral palsy exhibited the following adaptations during turning gait compared to the typically developing group: Stride length was decreased across all phases of the turn with largest effect size for the depart phase (2.02), stride width was reduced during the turn phase, but with a smaller effect size (0.71), and the average margin of stability during the approach phase of turning was reduced (effect size of 0.98). Few overall group differences were found for joint kinematic and kinetic measures; however, in many cases, the intra-subject differences between straight walking and turning gait were larger for the majority of children with cerebral palsy than for the typically developing children.

Interpretation: In children with cerebral palsy, turning gait may be a better discriminant of pathology than straight walking and could be used to improve the management of gait abnormalities.

Nomenclature

ANOVA	Analysis of variance
BOS	Base of support
COM	Center of mass
COM_{MIN}	The minimum medio-lateral distance between the COM and the lateral edge of the BOS
COM_{AV}	The average medio-lateral distance between the COM and the lateral edge of the BOS
CP	Cerebral Palsy
d	Cohen's d
FF/HF	Forefoot with respect to hindfoot
FO	Foot off
FS	Foot strike
GRF	Ground reaction force
HF/TB	Hindfoot with respect to tibia
J_{ML}	GRF impulse in the medio-lateral direction
kTPS	Turning profile score (kinetic)
kTVS	Turning variable score (Kinetic)
kTVS AnkleP	kTVS for ankle power
kTVS HipAbd	kTVS for hip moment (coronal plane)
kTVS HipRot	kTVS for hip moment (transverse plane)
kTVS KneeRot	kTVS for knee moment (transverse plane)
kTVS KneeVal	kTVS for knee moment (coronal plane)
MOS	Margin of stability
MOS_{MIN}	The minimum medio-lateral distance between the xCOM and the lateral edge of the BOS
MOS_{AV}	The average medio-lateral distance between the xCOM and the lateral edge of the BOS
PiG	Plug-in Gait model
RMS	Root mean square
Spin turn	Turn performed using the inside limb, with respect to the turning direction
Step turn	Turn performed using the outside limb, with respect to the turning direction
STP	Spatio-temporal parameter
TD	Typically developing
TPS	Turning profile score (kinematic)
TVS	Turning variable score (kinematic)
TVS AnkleDF	TVS for ankle (sagittal plane)
TVS AnkleEve	TVS for ankle (coronal plane)
TVS FFootSup	TVS for FF/HF (coronal plane)
TVS HipAdd	TVS for hip (coronal plane)
TVS HipRot	TVS for hip (transverse plane)
TVS KneeFlx	TVS for knee (sagittal plane)
xCOM	Extrapolated COM
Δ	Glass's delta

1. Introduction

Turning while walking is crucial to activities of daily living (Glaister et al., 2007; Sedgman et al., 1994) and performed using an outside (step) or inside (spin) leg strategy (Hase and Stein, 1999). Although it is unclear which technique is favored by adults, spin turns are preferred in typically developing (TD) children (Dixon et al., 2013). Turns can be separated into approach, turn, and depart phases (Glaister et al., 2008). Investigations have focused on the 90° turn (Glaister et al., 2008; Romkes, 2012; Strike and Taylor, 2009; Taylor et al., 2005), presumably due to the ubiquity of this change in direction in the built environment. Research revealed that 90° turning gait induces biomechanical adaptations compared to straight walking in unimpaired populations such as young adults (Glaister et al., 2008; Hasan et al., 1991; Strike and Taylor, 2009; Taylor et al., 2005; Xu et al., 2006) and TD children (Dixon et al., 2013, 2014c).

Turning gait may help identify and manage walking deviations in populations with restricted gait ability, such as children with cerebral palsy (CP) (Desloovere et al., 2010). To date, little is known about how children with CP biomechanically adapt to the requirements of this task (Brégou-Bourgeois et al., 2014; Romkes, 2012).

Brégou-Bourgeois et al. (2014) suggested that children with CP modify spatio-temporal parameters (STPs) during turning to increase stability. In fact, children with CP take a longer path and time to turn 90° (Romkes, 2012) and an increased stance time to turn 180° (Brégou-Bourgeois et al., 2014), compared to TD children; however, in these studies, stability was not assessed directly. Bruijn et al. (2013b) showed that children with CP walk with reduced dynamic stability as measured by the Foot Placement Estimator. This method was validated, but requires a full body marker set. A review of stability measures suggested that the extrapolated center of mass (xCOM) concept of Hof (2008), which takes into account the velocity of the center of mass (COM) to determine a margin of stability (MOS), represents a worthy alternative (Bruijn et al., 2013a). This approach is popular in stability studies (Beltran et al., 2014; Caderby et al., 2014; Hak et al., 2013; Mersmann et al., 2013).

Lower-limb joint kinematics and kinetics also show differences during turning gait, compared to straight walking in adults (Taylor et al., 2005; Xu et al., 2006) and in TD children (Dixon et al., 2013, 2014c). As these metrics are often clinically assessed in straight walking for children with CP, analysis of these quantities during real-word turning tasks may also be warranted. Reporting of these measures over the gait cycle via composite scores such as the Gait Variable Scores and Gait Profile Score of Baker et al. (2009) is popular and provides clinicians with a single number from which to assess gait. Analogous scores for turning have not yet been proposed.

Ground reaction force (GRF) may also quantify turning. In particular, the analysis of GRF impulse estimates the overall effect of the GRF in accelerating the COM. In healthy adults, medio-lateral GRF impulse (J_{ML}) was found to increase during 90° step turns compared to straight walking (Glaister et al., 2008; Strike and Taylor, 2009). In transtibial amputees, J_{ML} directed radially inward was decreased compared to controls for the inside limb during circle walking (Segal et al., 2011; Ventura et al., 2011). Segal et al. (2011) suggest that this adaptation minimizes the COM acceleration in the direction of the turn.

The aforementioned metrics can identify pathology in children with CP during straight walking. Therefore, changes to these measures in children with CP, compared to TD children, need to be different or disproportionately larger during turning gait, compared to straight walking, to warrant clinical implementation. Consequently, the aim of this study was to determine if these parameters could better identify gait deviations in children with CP during turning gait compared to straight walking. It was hypothesized that the following adaptations from normative data occur in an amplified manner during 90° turning for children with CP, compared to straight walking based on the perceived reduction in stability and typical CP related gait deviations: (1) for STPs, decreased stride velocity and stride length, as well as increased stance time and stride width (2) increased MOS, (3) decreased J_{ML}, and (4) worsened joint kinematics, moments, and power as measured by summary scores. Knowledge of turning gait adaptations provide further insight into gait control mechanisms and may lead to improved management of walking disorders in children with CP.

2. Methods

2.1 Subjects

Twenty-two children with CP (CP group) and fifty-four TD children (TD group) were recruited into this study. For the CP group, inclusion criteria were confirmed diagnosis of spastic diplegic CP and a Gross Motor Classification System (Palisano et al., 1997) score of 1 or 2. The exclusion criteria for the TD group were any history of gait or musculo-skeletal abnormalities. The local ethics committee approved this study and all children provided written assent/consent before participation. Data related to kinematic and kinetic quantities are based on a subset of children (Table 1) due to marker occlusions or missing GRF data. For the TD group, younger subjects were removed to ensure well-matched groups (all anthropometrics similar with $p \geq 0.056$). Anthropometrics, surgical history, and gait pattern, as determined by the algorithm of Sangeux et al. (2014), are provided for each child in the CP group (Supplementary Table 1).

2.2 Data collection

Subjects were fit with the Oxford Foot Model (Stebbins et al., 2006) and either the lower-limb (CP group) or full-body (TD group) Plug-in Gait (PiG) (Kadaba et al., 1990) markers and completed straight walking trials before performing 90° turning gait trials (left and right) (Supplementary Fig. 1). Based on the clinical gait analysis recommendations for the children in the CP group, the upper-body PiG markers were not used. Positions of markers were recorded at 100 Hz via a 12–16 camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK) which also synchronized GRF data (1000 Hz) from three force plates (OR-6, Advanced Mechanical Technology Inc., Watertown, USA) embedded in a 10.0 m walkway. All subjects freely chose their walking speed, starting foot, foot placement strategy, and turning radius, but start position was varied to capture GRF data.

2.3 Identification of turning strategies

Turn style was identified based on pelvic rotation (Dixon et al., 2013). In the complete TD group (n = 54), 43% of subjects only performed spin turns, 56% performed both step and spin turns, and a single subject solely performed step turns. For the CP group, no child chose to solely perform step turns. The CP group performed 142 spin and 30 step turns with 55% of subjects choosing both strategies and 45% only performing spin turns. As spin turns were the main strategy used by both groups, step turns were not analysed further.

2.4 Initial data processing

Initial data processing (marker gap filling, trajectory filtering, knee flexion/extension axis optimization (Baker et al., 1999)) and computation of hip and knee kinematics and kinetics as well as hindfoot with respect to tibia (HF/TB) and forefoot with respect to hindfoot (FF/HF) kinematics were conducted using Vicon Nexus (v1.8.4, Vicon Motion

Systems Ltd., Oxford, UK). Then, the *c3d* files were imported into Matlab (v2012b, The Mathworks Inc., Natick, USA) using the open-source Zoosystem Toolbox (Dixon et al., 2014b) where GRF data were processed as in Dixon et al. (2014c) and foot strike (FS) and foot-off (FO) events were identified (Zeni et al., 2008). Events were used to partition the data and identify turning phases with steps 2, 3, and 4 representing the approach, turn, and depart steps, respectively (Fig. 1). A minimum of 4 trials were collected for each condition. A single representative trial was retained for analysis as in our previous work using these datasets (Dixon et al., 2013, 2014c).

2.5 Derivation of gait metrics

STPs were estimated using the approach of Huxham et al. (2006) for non-linear gait. Stride length and stride width were leg-length normalized (Hof, 1996), but stride velocity and stance time were not normalized (Dixon et al., 2014a). Dynamic stability was measured by computing the xCOM. Briefly, to compute the xCOM, a vector quantity proportional to the velocity of the COM is added to the position of the COM (Hof et al., 2005). Here, the sacral marker was used to estimate the COM position for all subjects under analysis. The distal fifth metatarsal and lateral calcaneus markers outlined the lateral edge of the base of support (BOS) (Beltran et al., 2014; Gates et al., 2013). The distance between the xCOM and the lateral edge of the BOS defined the MOS (Hof et al., 2005). Medio-lateral MOS minimum (MOS_{MIN}) and average (MOS_{AV}) during the single-limb support phase of straight walking as well as the approach, turn, and depart phase of spin turns were evaluated. The medio-lateral distance between the position of the COM and the lateral edge of the BOS was also computed. Minimum (COM_{MIN}) and average (COM_{AV}) values were evaluated. The GRF data were transformed to a pelvis based coordinate system as in (Dixon et al., 2014c) to compute J_{ML} relative to the body over the entire approach and turn stance phase. Three-dimensional joint moments for the HF/TB were computed over the stance phase (Dixon et al., 2014c). As in Baker et al. (2009), the root mean square (RMS) difference between a subject's gait curve and the mean normative curve was computed and used to build kinematic and kinetic turning variable scores (TVS and kTVS, respectively). The curves corresponding to zones where major differences between straight walking and spin turns were reported in TD children (Dixon et al., 2013, 2014c) were extracted, i.e., the stance phase of the ipsilateral limb during the turn step (FS3 to FO3 in Fig 1. b). For the TVS, hip coronal (TVS HipAdd) and transverse (TVS HipRot), knee sagittal (TVS KneeFlx), HF/TB sagittal (TVS AnkleDF) and coronal (TVS AnkleEve), and FF/HF coronal (TVS FFootSup) plane angles of the ipsilateral (inside) limb were used. For kTVS, ankle power (kTVS AnkleP) as well as knee valgus (kTVS KneeVal), knee rotator (kTVS KneeRot), hip abductor (kTVS HipAbd), and hip rotator (kTVS HipRot) moment curves were extracted. The RMS average of all TVS and kTVS (AnkleP excluded for unit consistency) values were computed to form kinematic and kinetic turning profile scores (TPS and kTPS, respectively).

2.6 Statistical analysis

For all dependent variables, an analysis of variance (ANOVA) was implemented. For the STP and stability measures (stride velocity, stance time, stride length, stride width, MOS_{MIN}, MOS_{AV}, COM_{MIN}, and COM_{AV}), the model included the between-subject factor group (CP and TD) and within-subject factor condition (straight, spin approach, spin turn, and spin depart) (2 × 4 mixed ANOVAs). For J_{ML}, two conditions were explored for the contralateral (straight and spin approach) and ipsilateral (straight and spin turn) limb (2 × 2 ANOVAs). Similarly, for the kinematic and kinetic scores (TVS, kTVS, TPS, and kTPS), two conditions were assessed (straight and turn phase of spin) (2 × 2 ANOVAs). For the condition factor, main and simple main effects were not explored, as those analyses did not directly test study hypotheses. If heterogeneity was suspected, the Greenhouse-Geisser corrected p-value was reported for the main two-way ANOVAs. For follow-up simple main effect tests, Q-Q plots verified normality, while homogeneity of error variance was assessed by Levene's test. Failure of parametric assumptions led to the use of the Wilcoxon rank-sum test, otherwise unpaired t-tests were performed (Kirkwood and Stern, 2003). In the case of the follow-up simple main effect tests, a Bonferroni correction was applied. If corrections led to non-significant simple group effects, trends were reported. Effect size, Cohen's d (d) under parametric assumptions and Glass's delta (Δ) otherwise, were computed. ANOVA procedures and Mauchley's test were implemented in SPSS (v21, IBM Corp., Armonk, USA). Other statistical analyses were performed in Matlab (v2012b, The Mathworks Inc., Natick, USA). All tests were performed at the $\alpha = 0.05$ level. Bar graphs show means and confidence intervals. The effect of turning on the dependent variables was also assessed on a subject-by-subject basis to reflect use in clinical practice.

3. Results

3.1 Spatio-temporal parameters

All STPs required the Greenhouse-Geisser correction to the interaction p-values (Mauchley's test $p < 0.001$). Stride velocity and stance time revealed no significant group × condition interactions ($p = 0.233$ and $p = 0.377$, respectively). A significant group main effect revealed that the CP group reduced their stride velocity across all conditions, compared to the TD group ($p < 0.001$) (Fig. 2 a). For stance time, the main effect for group was non-significant ($p = 0.130$) (Fig. 2 b). Significant group × condition interactions were found for the spatial parameters of stride length ($p = 0.002$) and stride width ($p < 0.001$). For stride length, the simple main effect of group showed significant differences across all paired comparisons ($p \leq 0.001$). Effect sizes for the straight and spin approach conditions were similar (d = 1.17 and d = 1.19, respectively), but smaller for the turn (d = 0.91) and larger for the depart (Δ = 2.02) phases (Fig. 2 c). For stride width, simple group main effect tests revealed an increase during straight walking ($p = 0.001$ and Δ = 1.46), but decrease during the spin turn phase ($p = 0.003$ and Δ = 0.71) for the CP group compared to the TD group (Fig. 2 d).

3.2 Dynamic stability

For dynamic stability measures, homogeneity of variance was not assumed (Mauchley's test $p \leq 0.045$). For MOS_{MIN}, a significant group × condition interaction was identified ($p = 0.040$), but the depart phase only trended toward larger MOS_{MIN} for the CP group (Fig. 3 a). For MOS_{AV}, a significant group × condition interaction ($p = 0.020$) led to identification of decreased values for the CP group compared to the TD group during the approach phase of the turn via a simple main effect test ($p = 0.002$ and d = 0.98) (Fig. 3 b). Both COM_{MIN} and COM_{AV} showed significant group × condition interaction effects ($p < 0.001$ and $p = 0.002$, respectively). For COM_{MIN}, the COM was positioned more laterally with respect to the BOS for the CP group compared to the TD group during the spin turn phase ($p < 0.001$ and d = 1.39) (Fig. 3 c). For COM_{AV}, the CP group showed a greater medially oriented COM with respect to the BOS during straight walking ($p = 0.048$ and Δ = 1.03), while during the turn ($p < 0.001$ and Δ = 1.56) and depart ($p = 0.044$ and Δ = 1.56) phases the COM was shifted less laterally, compared to the TD group (Fig. 3 d).

3.3 Impulse

There were significant group × condition interactions for the contralateral and ipsilateral J_{ML} ($p = 0.002$ and $p < 0.001$, respectively). For the contralateral limb, simple main effect tests showed that the CP group decreased J_{ML} medially during the approach phase of turning, compared to the TD group ($p = 0.010$ and $d = 0.96$) (Fig. 4 a). For the ipsilateral limb, J_{ML} in the lateral direction was significantly reduced for the CP group during the spin turn phase compared to the TD group ($p < 0.001$ and $d = 1.56$) (Fig. 4 b).

3.4 Joint kinematics and kinetics

All group × condition interactions for the TVS and TPS values were found to be non-significant ($p \geq 0.438$); however, follow-up main effect tests showed significant increases in all measures for the CP group, as expected ($p < 0.014$). Subject-level analyses showed that the RMS difference from TD group data during turning was increased for many subjects in each TVS parameter and the overall TPS metric (Fig. 5 a—f and g, respectively). For the kTVS and kTPS analyses, a significant group × condition interaction was observed only for kTVS HipRot ($p = 0.005$). Follow-up group simple main effect test found that kTVS HipRot was greater for the CP group only during straight walking ($p < 0.001$ and $\Delta = 2.47$). A trend towards greater differences in the CP group was found for turning. For the remaining kTVS variables and kTPS, group main effect revealed increased difference for the CP group compared to the TD group, regardless of condition ($p \leq 0.042$). At the subject-level, RMS difference from the TD group data was increased for many children with CP during turning compared to straight walking (Fig. 5 h—m and n, respectively).

4. Discussion

This study investigated STPs, dynamic stability measures, impulse, joint kinematics, and joint kinetics of turning in children with CP. For many metrics, turning gait was a better discriminant of pathology than straight walking, suggesting that turning gait may be relevant for clinical gait analysis.

4.1 Spatio-temporal parameters

All STPs for straight walking in the TD group were similar to normative data (Lythgo et al., 2009). The hypothesis for stride velocity could not be completely confirmed. Although it was found that the CP group decreased their speed compared to the TD group, they did so consistently across conditions. Thus, stride velocity during turning may not provide further insight than can be obtained from straight walking analysis. For stance time, contrary to our hypothesis, no changes were seen across conditions or group, suggesting that it is not a relevant parameter for the analysis of turning. As hypothesized, the manner in which stride length and stride width were modulated across conditions and group was found to be different (group × condition interactions). The CP group reduced their stride length during all conditions; however, the reduction was amplified during the depart phase, suggesting that children with CP might experience difficulty transitioning back towards the straight walking gait pattern. Stride width results show that the CP group approached the turn with a wider BOS only to reduce their stride width during the turn, compared to the TD group. This strategy might improve stability in the early turning phase, but may lead to a risk of tripping as the feet are brought closer together as the turn progresses.

4.2 Dynamic stability

The MOS_{MIN} values during straight walking for the TD group were similar to those reported by others (Beltran et al., 2014; Gates et al., 2013). For straight walking, stability may be compromised in children with CP (Bruijn et al., 2013b); however, here MOS_{MIN} was unable to detect any significant differences. An increase in COM_{AV}, in agreement with Hsue et al. (2009), and other kinematic changes may have resulted in the CP group exhibiting similar dynamic stability to the TD group for straight walking. During turning, different strategies were implemented. For the approach phase, the CP group maintained a smaller MOS_{AV} than the TD group, despite larger COM-BOS distance (not significant). This suggests that TD children take advantage of velocity to prepare for turning, while children with CP are more reliant on body orientation. After this initial maneuver, the CP group did not lean as far laterally as the TD group. Possibly, the early medial lean technique is implemented to avoid having to lean further laterally in the later phases of turning. In the study of Romkes et al. (2012), the COM remained within the BOS throughout the turn for most children with CP (9/13); however, turn style and specific gait deviations in the group were not reported. Despite changes in COM position, both groups showed similar MOS in the final turning stages.

4.3 Impulse

The magnitude of J_{ML} during straight walking in the TD group agrees with the literature (Glaister et al., 2008). The current J_{ML} results for the spin turn phase (inside limb) are oriented in the same direction, but larger than those for the approach of the step turn (inside limb) of Glaister et al. (2008). This result is expected given the more dynamic nature of spin turns. As hypothesized, J_{ML} was reduced for the CP group, compared to the TD group. As impulse is related to momentum change (impulse-linear momentum theorem), it appears that children with CP turn without modifying their medio-lateral momentum as much as their TD peers. All impulse values remained similar across groups for straight walking, but showed unique changes during turning (decreased for CP group), suggesting that this metric may be clinically relevant.

4.4 Joint kinematics and kinetics

The straight walking kinematics and kinetics used herein and reported for the TD group in Dixon et al. (2013) and Dixon et al. (2014c), respectively, are consistent with normative data (Schwartz et al., 2008). As hypothesized, the TVS, kTVS, TPS, and kTPS were able to identify unique adaptations to turning gait in the CP group; however, all fared better in the subject-level analyses than the group based (statistical) investigations. The reasons for these adaptations remain unclear. Therefore, attempting to normalize scores towards normative values may not be warranted, rather monitoring of scores pre- and post-intervention may be more appropriate.

4.5 Clinical applications

Straight walking analysis can inform decision making when gait deviations are substantial; however, if analysis reveals only minor differences compared to normative data, despite a child's reported difficulty in daily locomotor activities, turning protocols may be considered. All variables described in this study, while not possessing the ability to discern amplified or different adaptations in the entire cohort, could be used to guide treatment options, monitor progression in gait ability during pre- and post-operative gait assessments, and provide indication of treatment outcomes on a subject-by-subject basis. Consideration of a patient's specific gait difficulties would best guide parameter selection for clinical examination. Summary scores could be visualized using charts as in Fig. 1 of Baker et al. (2009) or using standard gait curves. Finally, while clinical interpretation of the results for each child with CP is outside the scope of this study, it is important to highlight that the overall TPS and kTPS do not show consistent trends across subjects. Both scores may be important for turning gait analysis.

4.6 Limitations

Five limitations require consideration. First, eighteen children with CP had different gait patterns for each limb (Supplementary Table 1); yet, sides were combined for analysis. Thus, the current approach may be misleading for subjects with important gait asymmetries. The choice to investigate side differences should be determined on a case-by-case basis. Second, only spin turns were investigated as most children from both groups preferred this turn style. These results are in agreement with work in older adults where step turns only dominate during fast walking (Akram et al., 2010), suggesting that spin turns are not overly difficult to perform for children with CP. It remains unclear if speed, disability, or age, dictate the choice of strategy. A similar analysis could be performed using normative step turn data. Evolution from a step to spin turn strategy on its own may be a sign of improved mobility. Third, for the kinetics, information from the depart step was not available. Future studies could add an obliquely positioned force plate or start trials perpendicular to the gait walkway to capture this information. Also, in some cases, different subjects were analysed for the approach and turn phase of turning and for straight walking in order to maximize the sample size. Therefore, differences may be related both to condition and subject investigated. Finally, only ipsilateral limb joint kinetic parameters were studied. Analysis of the contralateral side might also reveal interesting adaptations.

5. Conclusions

Turning gait may better approximate daily walking tasks of children with CP and may be implemented in clinical practice as a supplement to straight walking analysis. Turning anaylsis may identify abnormal motion patterns not evident in straight walking, better inform treatment options, and improve the assessment of treatment outcomes.

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7. Appendix

Supplementary spin turn data (TD group) are available on-line.

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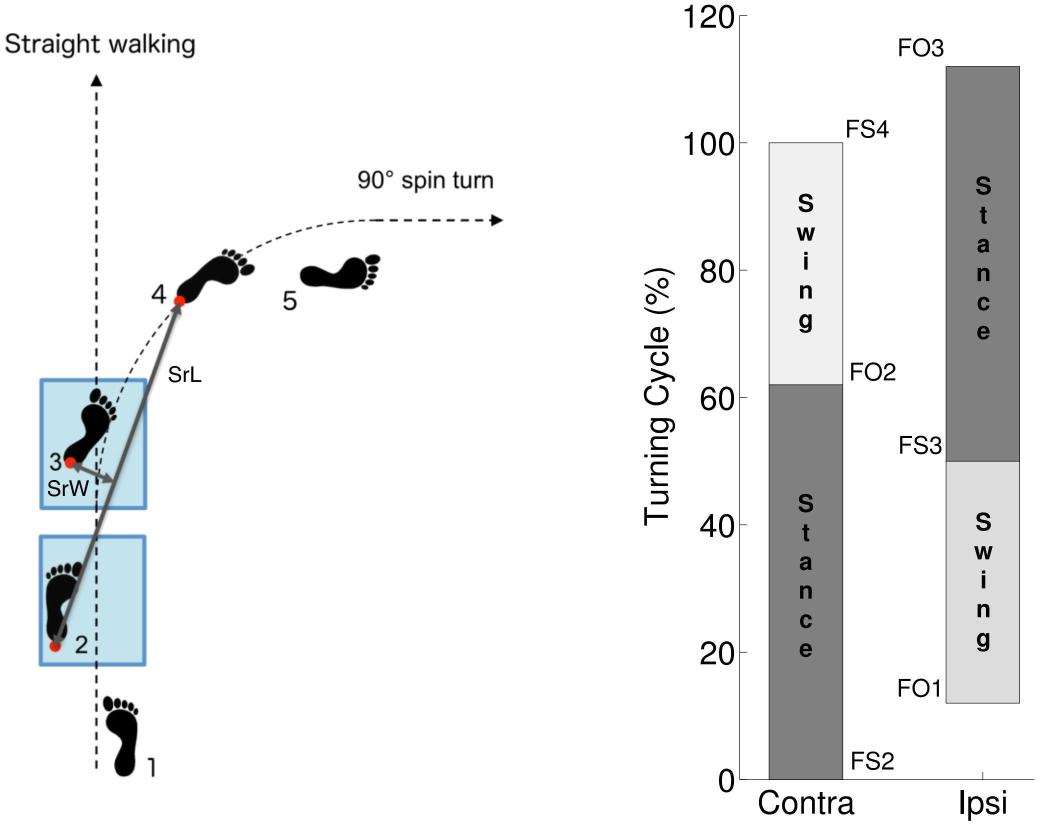


(a) (b)

Fig. 1: Diagrammatic representation of (a) a 90° spin turn to the right with steps 2, 3, and 4 corresponding to the approach, turn, and depart phase, respectively. The turn phase stride length (SrL), and stride width (SrW) as well as the approximate placement of force plates (shaded rectangles) shown. (b) Foot-strike (FS) and foot-off (FO) events as a percentage of the turning cycle (162% of the gait cycle). The inside limb is taken to be ipsilateral (Ipsi), while the outside limb is contralateral (Contra).

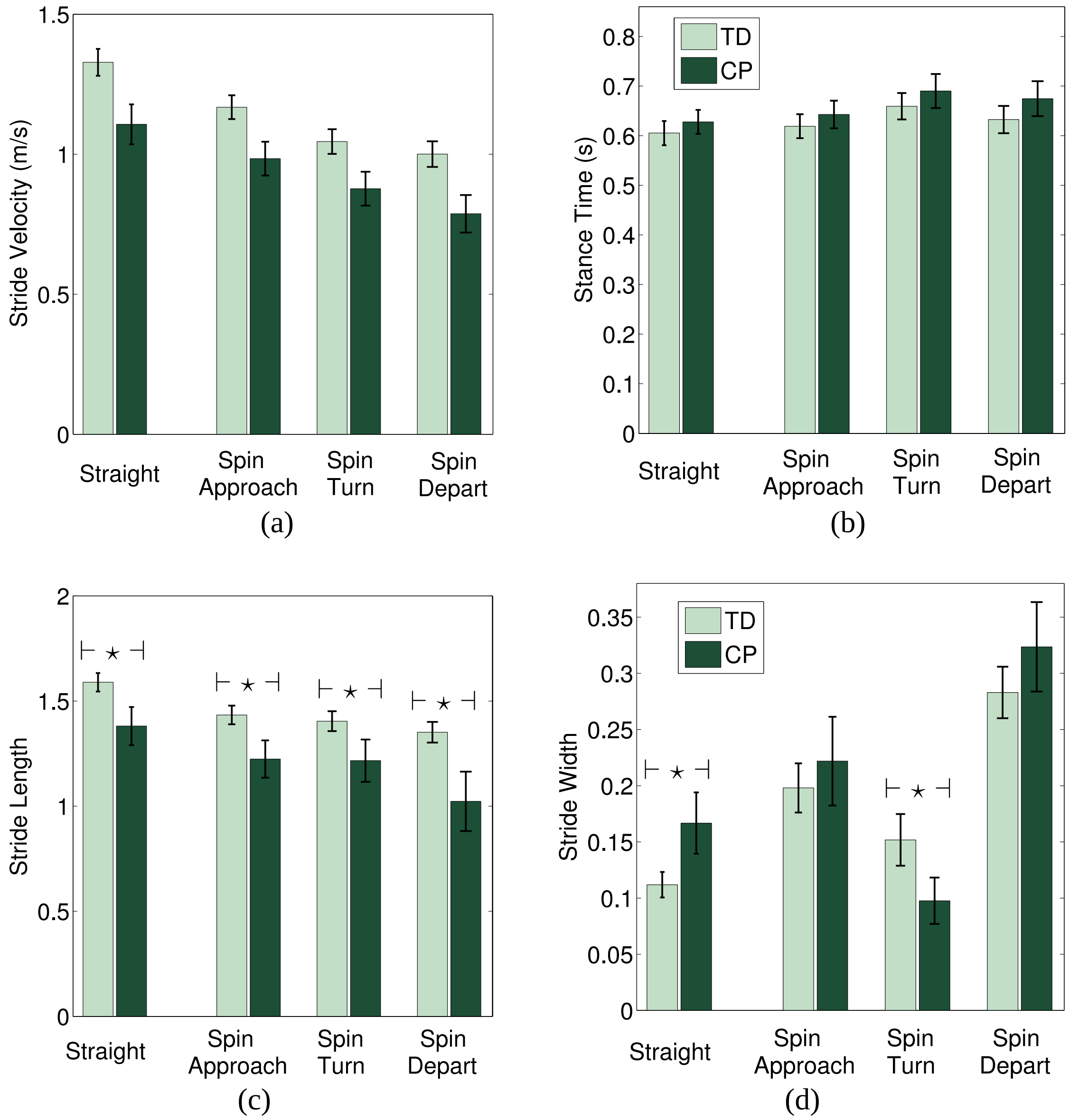


Fig. 2: Spatio-temporal parameters of (a) stride velocity, (b) stance time, (c) stride length and (d) stride width across group and condition for children with cerebral palsy (CP) and their typically developing peers (TD). Significant group simple main effects (*) shown.

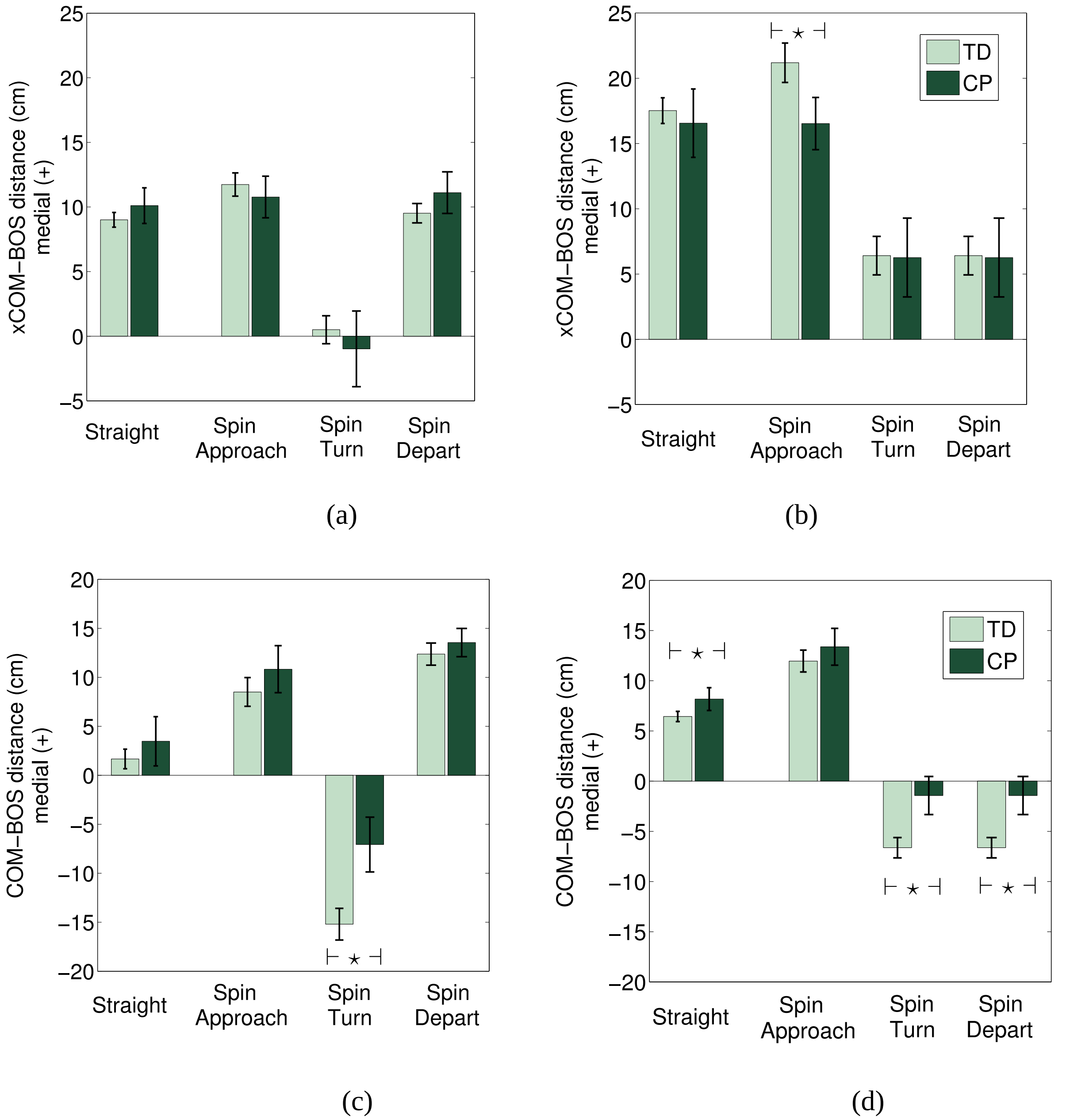
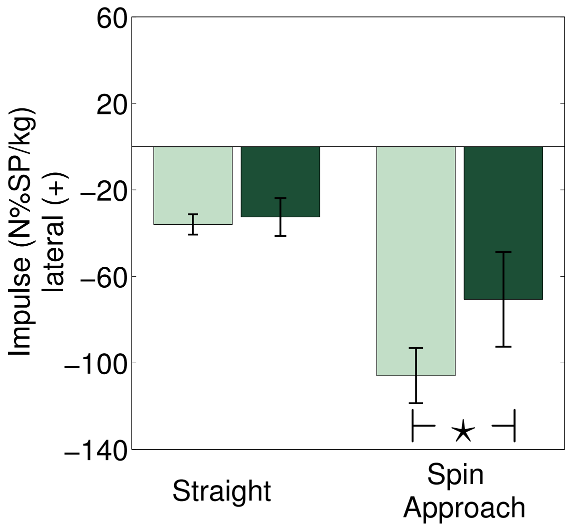
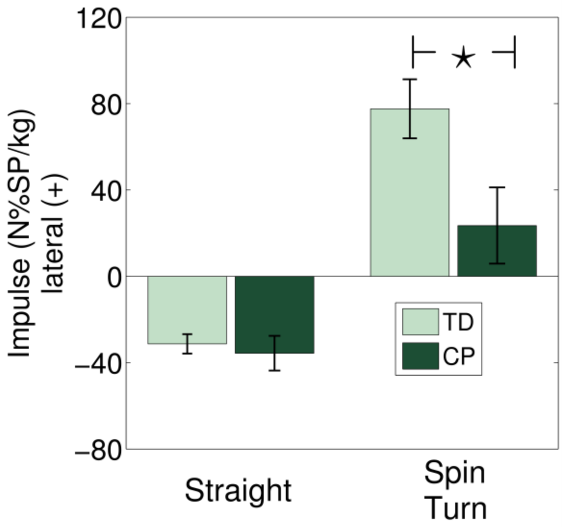


Fig. 3: Extrapolated center of mass to base of support (xCOM-BOS) medio-lateral (a) minimum (MOS_{MIN}) and (b) average (MOS_{AV}) and center of mass to base of support (COM-BOS) medio-lateral (c) minimum (COM_{MIN}) and (d) average (COM_{AV}) distance across group and condition for children with cerebral palsy (CP) and their typically developing peers (TD). Significant group simple main effects (*) shown.



(a)



(b)

Fig. 4: Total medio-lateral impulse over the stance phase (SP) for the (a) contralateral (approach phase) and (b) ipsilateral (turn phase) limb across group and condition for children with cerebral palsy (CP) and their typically developing peers (TD). Significant group simple main effects (*) shown.

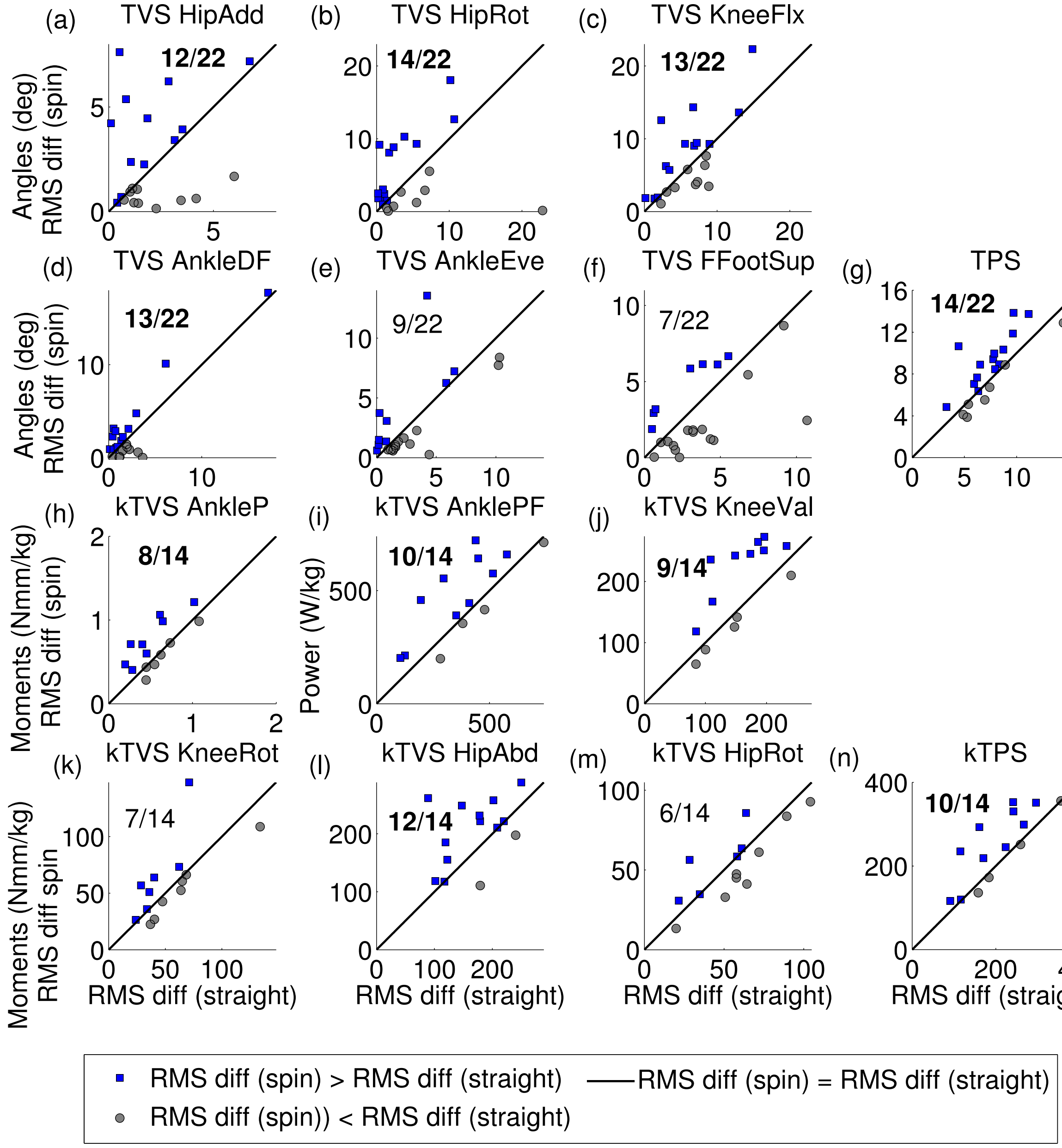
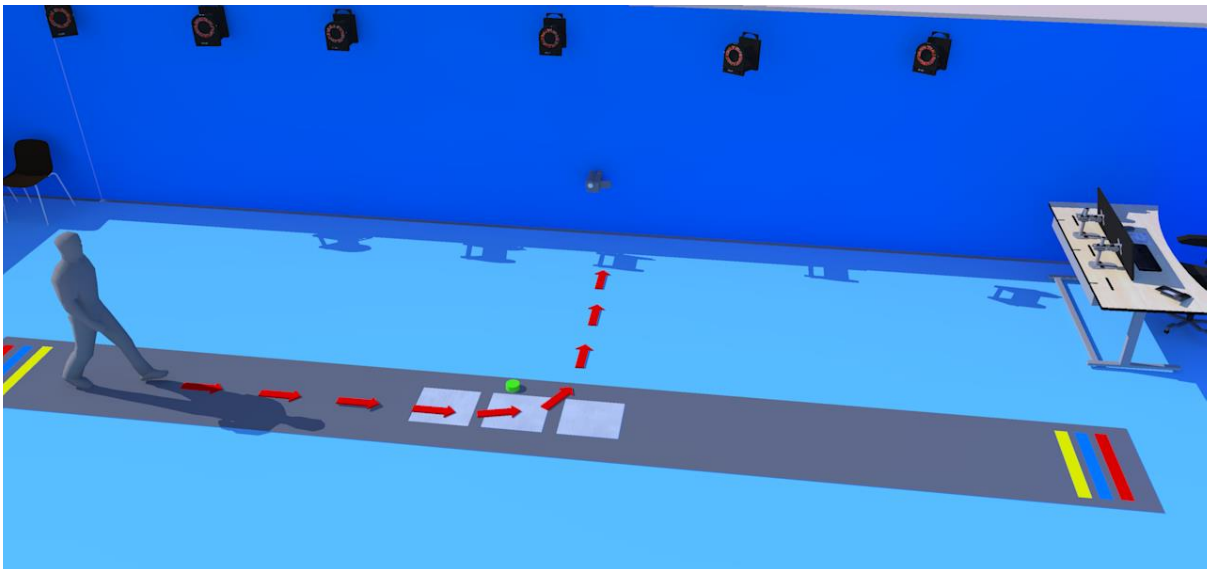


Fig. 5: Kinematic Turning Variable Scores (TVS) (a—f) and Turning Profile Score (TPS) (g) as well as kinetic Turning Variable Score (kTVS) (h—m) and kinetic Turning Profile Score (kTPS) (n) during straight and turning conditions for each child with cerebral palsy (CP). Bold font for proportion where most children with CP had an increased difference from the typically developing group during turning (spin).

Table 1: Anthropometrics for children with cerebral palsy and their typically developing peers

Group	***n***	**Age (years)**	**Weight (kg)**	**Height (cm)**	**Leg-length (cm)**	**Sex**
CP-kinematic	22	12.4 (2.8)	41.9 (13.7)	149.7 (17.7)	79.0 (9.9)	8F, 14M
CP-kinetic	18	12.7 [11.4 –14.1]	42.9 (13.8)	151.4 (16.8)	80.1 (9.3)	6F, 12M
TD-kinematic	44	11.0 [10.2 –11.8]	40.7 (13.9)	149.1 (15.5)	78.8 (8.8)	21F, 23M
TD-kinetic	41	11.3 [10.5 – 2.1]	42.5 (13.4)	151.3 (15.0)	80.4 (8.3)	18F, 23M

Mean (standard deviation) or median [95% confidence interval] for normally or non-normally distributed data, respectively. Anthropometrics presented for kinematic and kinetic analysis subgroups in children with cerebral palsy (CP) and their typically developing (TD) peers. Sample size (*n*) and sex (female (F) and male (M)) also shown.



Supplemental Fig. 1: Graphical representation of experimental set-up within the gait laboratory. Subjects were instructed to walk around a small green object near the center of the space and turn towards a digital camera positioned perpendicular to their original direction of progression. No marks were made on the floor, but subjects generally followed the path shown by the red arrows. Figure created in SketchUp (v.14 Trimble Navigation, Ltd., Sunnyvale, USA) and rendered via Kerkythea (Solid Iris Technologies, Haidari, Greece).

Supplementary Table 1: Anthropometrics and surgical history of all children in the cerebral palsy group

Subject	**Sex**	**Age** (years)	**Mass** (kg)	**Height** (cm)	**Leg-length** (cm)	**GMFCS**	**Gait Pattern**		**Last Intervention** (years)	**Intervention details**
C0635E	M	14	70.0	175.0	91.0	2	Mild	Mild	4.3	L gast lengthening
C0701E	F	12	44.0	145.0	78.0	2	Mild	N/C	-	-
C0716D	M	14	45.0	168.0	94.0	2	Jump	Mild	-	-
C0831D	M	16	72.0	178.5	95.3	1	Mild	Mild	1.0	R femoral de-rotation osteotomy R distal tibia osteotomy R+L hams and R+L gast lengthening
C0842E	M	16	58.0	118.0	60.0	2	Crouch	App Eq	0.5	R+L hams and R+L gast botox
C0850G	F	11	37.0	150.0	77.8	2	Jump	App Eq	2.5	R+L femoral de-rotation osteotomy R+L rectus femoris transfer R+L hams and L gast lengthening
C1090C	F	8	33.0	130.0	71.0	2	Jump	Mild	2.5	R gast lengthening
C1171B	M	9	26.0	135.5	71.0	2	Jump	N/C	2.5	R+L plantarflexor lengthening
C1215B	F	8	23.0	118.0	60.0	1	True Eq	Mild	0.7	L serial casting
C1268A	M	15	53.0	171.0	88.8	2	N/C	True Eq	-	-
C1270A	M	12	32.0	141.0	77.5	2	N/C	Mild	-	-
C1313A	F	10	32.0	150.0	83.0	2	Mild	Mild	-	-
C1314A	M	12	34.0	140.0	74.0	1	N/C	True Eq	unknown	R+L hams and gast botox
C1318A	M	9	28.0	134.0	68.0	1	Mild	True Eq	-	-
C1320A	F	18	50.0	148.0	77.0	2	True Eq	True Eq	8	R+L gast botox
C1393A	F	10	31.0	142.5	73.0	1	Jump	True Eq	6 2	R+L serial casting
C1423A	F	14	44.0	157.0	82.3	1	N/C	True Eq	1.8	R gast botox
C1424A	M	12	33.0	143.0	75.5	1	Mild	App Eq	1.0	R+L hams and gast botox
C1495A	M	11	32.0	146.0	77.0	2	Mild	True Eq	-	-
C1499A	M	16	59.5	174.0	92.5	1	Crouch	N/C	-	-
C1500A	M	14	44.8	171.0	86.8	1	N/C	Jump	-	-
N0258B	M	12	40.0	157.0	84.0	1	Mild	Mild	-	-

Anthropometric and clinical information for female (F) and male (M) children with cerebral palsy. Main interventions: lengthening of right (R) and (L) hamstrings (hams) and gastrocnemius (gast) or Botulinum Toxin injections (botox). Gait patterns: true and apparent (App) Equinus (Eq), jump, crouch, mild, and non-classified (N/C). Gross Motor Classification System (GMFCS) level also shown. Last intervention column lists time (years) between last intervention and clinical gait analysis exam.