Deliberately light Interpersonal contact affects the control of head stability during walking in children and adolescents with cerebral palsy

Schulleri, Katrin Hanna; Burfeind, Frauke; Höß-Zenker, Beate; Feketené Szabó, Eva; Herzig, Nadine; Ledebt, A.; Johannsen, Leif

published in
Archives of Physical Medicine and Rehabilitation
2017

DOI (link to publisher)
10.1016/j.apmr.2017.01.026

document version
Publisher's PDF, also known as Version of record

Archives of Physical Medicine and Rehabilitation

journal homepage: www.archives-pmr.org

Archives of Physical Medicine and Rehabilitation 2017;98:1828-35

ORIGINAL RESEARCH

Deliberately Light Interpersonal Contact Affects the Control of Head Stability During Walking in Children and Adolescents With Cerebral Palsy

Katrin Hanna Schulleri, MSc,[a] Frauke Burfeind, MSc,[b] Beate Höß-Zenker, PhD,[c] Éva Feketené Szabó, PhD,[d] Nadine Herzig, MD,[e] Annick Ledebt, PhD,[f] Leif Johannsen, PhD[a,g]

From the [a]Department of Sport and Health Science, Technical University Munich, Munich, Germany; [b]Department of Human Movement Sciences, VU University Amsterdam, Amsterdam, The Netherlands; [c]Phoenix GmbH, Conductive Education of the Pfennigparade Foundation, Munich, Germany; [d]András Pető College, Budapest, Hungary; [e]Center for Children and Neuroorthopaedics, Schön Klinik München Harlaching, Munich, Germany; [f]MOVE Research Institute Amsterdam, Amsterdam, The Netherlands; and [g]School of Health Sciences, University of East Anglia, Norwich, United Kingdom.

Abstract

Objective: To evaluate the potential of deliberately light interpersonal touch (IPT) for reducing excessive head and trunk sway during self-paced walking in children and adolescents with cerebral palsy (CP).

Design: Quasi-experimental, proof-of-concept study with between-groups comparison.

Setting: Ambulant care facility, community center.

Participants: Children and adolescents (N=65), consisting of those with CP (spastic and ataxic, n=26; Gross Motor Function Classification System I–III; mean age, 9.8y; 11 girls, 15 boys) and those who were typically developed (TD, n=39; mean age, 10.0y; 23 girls, 16 boys).

Interventions: IPT applied by a therapist to locations at the back and the head.

Main Outcome Measures: As primary outcomes, head and trunk sway during self-paced walking were assessed by inertial measurement units. Secondary outcomes were average step length and gait speed.

Results: CP group: apex and occiput IPT reduced head velocity sway compared with thoracic IPT (both $P=.04$) irrespective of individuals' specific clinical symptoms. TD group: all testing conditions reduced head velocity sway compared with walking alone (all $P\leq.03$), as well as in apex and occiput IPT compared with paired walking (both $P\leq.02$).

Conclusions: Deliberately light IPT at the apex of the head alters control of head sway in children and adolescents with CP. The effect of IPT varies as a function of contact location and acts differently in TD individuals.

Archives of Physical Medicine and Rehabilitation 2017;98:1828-35

Severe gait deficits in individuals with cerebral palsy (CP) lead to an increased fall risk, with disabilities in activities of daily living and reduced social participation.[1] During walking, the motion of the trunk as the heaviest segment of the body strongly affects the locomotor pattern and requires active balance control.[2] Individuals with CP show a severe gait disorder in combination with noticeable abnormalities in trunk motion, which may be a genuine deficit and specific cause for gait instability in CP.[3,4] Impaired gross motor function is associated with a greater thorax range of motion during walking in CP.[5] Heyrman et al[6] reported that children with spastic diplegia and only mildly impaired gross motor function still show increased lateral bending of the trunk during gait, while more severely impaired children demonstrate an increased motion amplitude in all 3 spatial planes.

Any trunk motion during walking will perturb head orientation and thus cause significant vestibular stimulation unless neck

Supported by the Federal Ministry of Education and Research of Germany (BMBF; grant no. 01EO1401) and by the Deutsche Forschungsgemeinschaft through the TUM International Graduate School of Science and Engineering.

Disclosures: none.

0003-9993/17/$36 - see front matter © 2017 by the American Congress of Rehabilitation Medicine
http://dx.doi.org/10.1016/j.apmr.2017.01.026

articulation minimizes head motion. Compensatory head-on-trunk articulation during walking primarily serves head stability.[7] Minimizing head motion may therefore be a major goal of the postural control system during walking in order to align the horizontal semicircular canals of the vestibular system to the earth horizontal for facilitating the integration of vestibular and visual information.[8]

It is an open question how trunk control can be improved in children with CP. Vision and vestibular feedback play an important role, but they are not the only afferent signals that can be used for locomotor control. Somatosensory afferences as well as proprioceptive feedback are also used for controlling the gait cycle and body balance.[9] A review by Pavão et al[10] indicated that there was a lack of research on the benefit of somatosensory feedback for balance control in individuals with CP.

Researchers have become increasingly interested in the effect of nonplantar light tactile feedback on body control when contacting an external reference. The effect of light touch during standing and walking has been described in several patient populations.[11] In addition to the single-person concept of haptic sensory augmentation, interpersonal touch (IPT) is a category of haptic interactions very relevant and frequently used in clinical situations. Deliberately light IPT results in reduced sway and increased coordination of trunk sway between 2 individuals during quiet standing as well as voluntary swaying.[12,13] IPT reduces sway in patients with chronic stroke as well as Parkinson disease.[14] More rostral IPT (at shoulder level) reduces sway to a greater amount than more caudal (low back) locations,[14] which is analogous to single-person effects of light touch on body sway.[15,16] The observation that more cranial IPT results in more reduced sway could be caused by a clearer signal resulting from a greater sway amplitude at the contact point. Alternatively, an increased resemblance between the haptic and vestibular signals could facilitate a more accurate stability state estimation.[17]

This proof-of-concept study aimed to investigate the effect of IPT on the control of trunk sway and gait during walking in children and adolescents with CP. To assess the effects of IPT on locomotion without confounding movement impairments caused by CP, we tested age-matched typically developed (TD) participants. We hypothesized that reinforcement of the head as an inertial guidance platform[8,18] by IPT at more rostral locations would benefit the control of head and trunk sway in participants with and without CP.

Methods

Participants

A convenience sample of 26 children and adolescents (mean age ± SD, 9.8±4.5y; mean height ± SD, 134±22cm; mean weight ± SD, 34.3±18.5kg) with CP were recruited at 3 therapeutic institutions (Schön Klinik Harlaching, München; Phoenix Pfennigparade, München; Petö Institute, Budapest). Participants with CP needed a Gross Motor Function Classification System (GMFCS)[18] level of III or higher to participate. Individuals were excluded if any other impairments were reported that could either affect locomotion or communication. Another convenience sample of 39 TD individuals (mean age ± SD, 10.0±4.4y; mean height ± SD, 144±25cm; mean weight ± SD, 38.5±17.5kg) were recruited from the community as a control group. Table 1 shows the demographic and clinical information of all participants. The study was approved by the medical ethical committee of the Technical University of Munich, and all participants or their guardians gave written informed consent.

List of abbreviations:

CP cerebral palsy
GMFCS Gross Motor Function Classification System
HVS head velocity sway
IPT interpersonal touch
TD typically developed
TVS trunk velocity sway

Experimental procedure

Each participant took part in a single 45-minute testing session. After demographic and medical data were collected, the child was familiarized with an inertial motion tracking system.[a] Four sensors of the system (60Hz) were fastened to both lower legs laterally, the sternum, and the forehead. After 2 practice trials, each participant walked at a self-chosen pace in a straight line for a distance of 10m between 2 measured floor markings, 6 times per testing condition. Participants were tested in 5 testing conditions in randomized order. IPT was applied by either a physical therapist or a conductor, who was trained in conductive education, in 3 conditions, while in the remaining 2 control conditions participants walked without IPT. The 5 testing conditions were as follows: (1) walking alone; (2) walking with the physical therapist/conductor peripherally visible (paired walking); (3) IPT on the thoracic spine (between the scapulae); (4) IPT below the occiput; and (5) IPT slightly dorsal of the apex of the head. An overview of the IPT locations is presented in figure 1A.

Data reduction

Orientation of the inertial sensors in all 3 planes was processed unfiltered by a custom processing toolbox in Matlab (2014a).[b] Phases of steady-state walking were extracted by manually segmenting trials based on sensor data from the dominant leg to exclude turning points, gait initiation, and stopping from analysis. Gait speed and average step length were determined by dividing the walking distance by the time needed to cover it and the number of all steps detected during this period.

Head velocilty sway (HVS) and trunk velocity sway (TVS) were measured as the SD of the angular velocity of the respective sensor's orientation. To prevent angular flip-overs between $-180°$ and $180°$ from distorting the velocity sway measure, sensor orientation angles were cosine-transformed before differentiation ($\cos(\alpha)/s$; fig 1B). A direction-unspecific velocity sway measure was calculated for each sensor by taking the square root of the sum of squares of the velocity sway on each of the 3 axes of a sensor.

Statistical analysis

Statistical analysis was performed in IBM SPSS statistics 23.[c] All extracted parameters (gait speed, step length, HVS, TVS) were statistically analyzed using a mixed 2-factorial repeated-measures analysis of variance, with group as the between-subject factor (2 levels: CP vs TD participants) and testing condition as the within-subject factor (5 levels). Because of the participants' range in demographic parameters such as age, height, and weight, we used independent *t* tests as well as chi-square tests to assess differences in the sample averages and distributions between both participant

Table 1 Demographic and clinical information of all participants

Group	Participant	Age (y)	Height (cm)	Weight (kg)	Sex	Dominance	GMFCS	Symptom I*	Symptom II†
TD	1	14	175	60	M	R	NA	NA	NA
TD	2	11	149	37	F	R	NA	NA	NA
TD	3	13	160	52	M	L	NA	NA	NA
TD	4	15	186	68	M	L	NA	NA	NA
TD	5	17	169	53	F	R	NA	NA	NA
TD	6	11	149	41	F	L	NA	NA	NA
TD	7	13	165	58	F	R	NA	NA	NA
TD	8	9	146	32	F	R	NA	NA	NA
TD	9	6	126	25	F	R	NA	NA	NA
TD	10	6	126	26	F	R	NA	NA	NA
TD	11	9	151	42	F	R	NA	NA	NA
TD	12	7	123	25	M	R	NA	NA	NA
TD	13	8	137	35	F	R	NA	NA	NA
TD	14	11	159	38	F	L	NA	NA	NA
TD	15	14	170	50	M	R	NA	NA	NA
TD	16	9	140	30	M	R	NA	NA	NA
TD	17	8	128	22	F	R	NA	NA	NA
TD	18	12	152	46	M	R	NA	NA	NA
TD	19	11	148	38	F	R	NA	NA	NA
TD	20	5	111.5	20	M	R	NA	NA	NA
TD	21	17	176	63	F	R	NA	NA	NA
TD	22	12	180	50	M	L	NA	NA	NA
TD	23	13	165	46	F	R	NA	NA	NA
TD	24	11	150	44	M	R	NA	NA	NA
TD	25	10	148	37	M	R	NA	NA	NA
TD	26	13	166	59	F	R	NA	NA	NA
TD	27	4	110	18	M	R	NA	NA	NA
TD	28	17	188	83	M	R	NA	NA	NA
TD	29	18	170	60	F	R	NA	NA	NA
TD	30	8	130	28	F	R	NA	NA	NA
TD	31	5	116	22	F	R	NA	NA	NA
TD	32	19	174	65	M	L	NA	NA	NA
TD	33	6	107	16	F	R	NA	NA	NA
TD	34	3	100	17	M	L	NA	NA	NA
TD	35	6	120	20	F	R	NA	NA	NA
TD	36	4	108	21	F	L	NA	NA	NA
TD	37	6	119.5	20	F	R	NA	NA	NA
TD	38	6	124	17	F	R	NA	NA	NA
TD	39	4	102	16	M	L	NA	NA	NA
CP	1	7	116	17	M	R	I	4	2
CP	2	6	116	26	F	NA	III	4	2
CP	3	4	111	19	M	L	II	1	1
CP	4	6	118	18	F	R	I	1	1
CP	5	7	113	18	F	R	II	4	1
CP	6	4	107	15	F	R	II	2	1
CP	7	6	110	17	M	L	II	2	1
CP	8	6	121	26	F	L	I	1	1
CP	9	5	99	15	M	R	II	4	2
CP	10	12	145	43	F	NA	II	2	1
CP	11	10	141	44	F	L	II	2	1
CP	12	8	119	22	M	R	III	2	1
CP	13	9	139	27	F	NA	II	4	2
CP	14	14	162	44	M	L	II	3	1
CP	15	10	145	56	F	L	I	2	1
CP	16	12	141	29	M	L	III	2	1
CP	17	9	135	34	M	L	I	2	1
CP	18	13	164	61	M	L	I	2	1

(*continued on next page*)

Table 1 (*continued*)

Group	Participant	Age (y)	Height (cm)	Weight (kg)	Sex	Dominance	GMFCS	Symptom I*	Symptom II†
CP	19	10	145	38	M	R	II	2	1
CP	20	18	159	51	F	R	I	4	1
CP	21	8	112	20	F	L	II	2	1
CP	22	7	110	19	M	NA	III	2	1
CP	23	12	150	39	M	R	II	3	1
CP	24	19	171	84	M	R	I	1	1
CP	25	18	172	71	M	L	II	1	1
CP	26	18	163	38	M	L	II	2	1

Abbreviations: F, female; L, left; M, male; NA, not available; R, right.
* Symptom I: 1, unilateral; 2, bilateral leg; 3, bilateral arm; 4, bilateral complete.
† Symptom II: 1, spastic; 2, ataxic.

groups. The TD group tended to be taller by about 10cm ($t_{63}=1.70$, $P=.09$; $\chi^2_3=8.25$, $P=.04$). Therefore, we included height as a covariate in all analyses encompassing a comparison between both groups. Greenhouse-Geisser−corrected *P* values were used as a conservative statistical criterion. Level of significance was set to $P=.05$. Bonferroni-corrected post hoc comparisons between conditions were conducted as appropriate to resolve interactions between group and testing condition.

Additional statistical analyses were performed between subgroups of the CP participants according to GMFCS level (I/II/III) and impairment categorizations (spastic/ataxic; plegia: unilateral/bilateral leg/bilateral arm/bilateral complete). No differences between subgroups of the individuals with CP were found with respect to age, height, or weight with the exception that the individuals with ataxic CP were numerically younger and shorter (both $P\geq.11$).

Results

Gait speed and stride duration

Spontaneous gait speed was slower in the CP group (mean ± SD, 1.03±.29m/s; $F_{1,63}=13.60$, $P=.001$, partial $\eta^2=.19$) than in the TD group (mean ± SD, 1.32±.26m/s). An interaction between group and testing condition was found ($F_{4,252}=15.36$, $P<.001$, partial $\eta^2=.21$). In the CP group, the participants did not change their gait speed in any of the testing conditions. In contrast, the TD group walked slower in all 4 conditions compared with walking alone (mean ± SD, 1.41±.27m/s; all $P\leq.002$). Gait speed was still slower in occiput IPT (mean ± SD, 1.25±.26m/s) compared with thoracic IPT (mean ± SD, 1.30±.26m/s) and paired walking (mean ± SD, 1.34±.27m/s; both $P\leq.02$).

Average step length was shorter in the CP group (mean ± SD, 50±10cm; $F_{1,63}=13.84$, $P<.001$, partial $\eta^2=.20$) compared with the TD group (mean ± SD, 62±11cm). We also found an interaction between the group and testing condition ($F_{4,252}=9.30$, $P<.001$, partial $\eta^2=.14$). While no differences between testing conditions were found for the CP group, in the TD group step length was shorter in all 4 test conditions involving the physical therapist/conductor compared with walking alone (mean ± SD, 65±11cm; all $P\leq.03$). Thoracic (mean ± SD, 60±12cm) and occiput IPT (mean ± SD, 59±12cm) showed still shorter step length relative to paired walking (mean ± SD, 63±12cm; both $P\leq.006$).

For step length and gait speed, no general differences between subgroups or interactions with the testing condition were found for the subdivisions of the participants with CP. Exceptions were GMFCS level I tending to show the fastest gait speed (mean ± SD, 1.17±.27m/s), followed by level II (mean ± SD, 1.02±.22m/s) and level III (mean ± SD, .82±.41m/s; $F_{2,23}=2.52$, $P=.10$, partial $\eta^2=.19$).

Head and trunk velocity sway

HVS was greater in the CP participants ($F_{1,63}=15.98$, $P<.001$, partial $\eta^2\geq.21$) compared with the TD group (fig 2A). TVS only tended to be greater in the CP participants than the TD group ($F_{1,63}\geq3.04$, $P=.09$, partial $\eta^2\geq.05$) (fig 2B). For HVS and TVS, interactions were found between group and testing condition (both $F_{4,252}\geq3.54$, both $P\leq.03$, both partial $\eta^2\geq.06$). In the CP group, HVS was reduced in the occiput and apex IPT conditions compared with thoracic contact (both $P\leq.04$). Concerning the trunk, the thoracic IPT condition tended to show more TVS than apex IPT ($P=.06$). In the TD group, all other conditions showed less HVS compared with walking alone (all $P\leq.03$). In addition, occiput and apex IPT were still lower than paired walking (both $P\leq.02$). For the trunk, both apex and thoracic IPT tended to show lower TVS compared with walking alone (both $P\leq.09$).

The CP subgroups differed in terms of HVS, but no interactions between testing conditions and subgroups were found for either HVS or TVS. As an exception, an effect of GMFCS level on TVS was present ($F_{2,23}=3.60$, $P=.05$, partial $\eta^2=.25$). The participants with GMFCS level III showed the most variable TVS (mean ± SD, .45±.15), followed by level II (mean ± SD, .29±.17) and level I (mean ± SD, .21±.15).

Discussion

We aimed to investigate whether IPT at the head is a way to facilitate the control of body sway during walking in children and adolescents with CP and with typical development. The effect of IPT was assessed in terms of step length and gait speed as well as head and trunk velocity sway. In general, the CP and TD groups differed in gait speed and average step length. The TD group walked faster with longer average steps and less head and trunk velocity sway than the CP group. This is not unexpected since it is well known that individuals with CP show reduced gait speed with longer stride duration and increased postural instability.

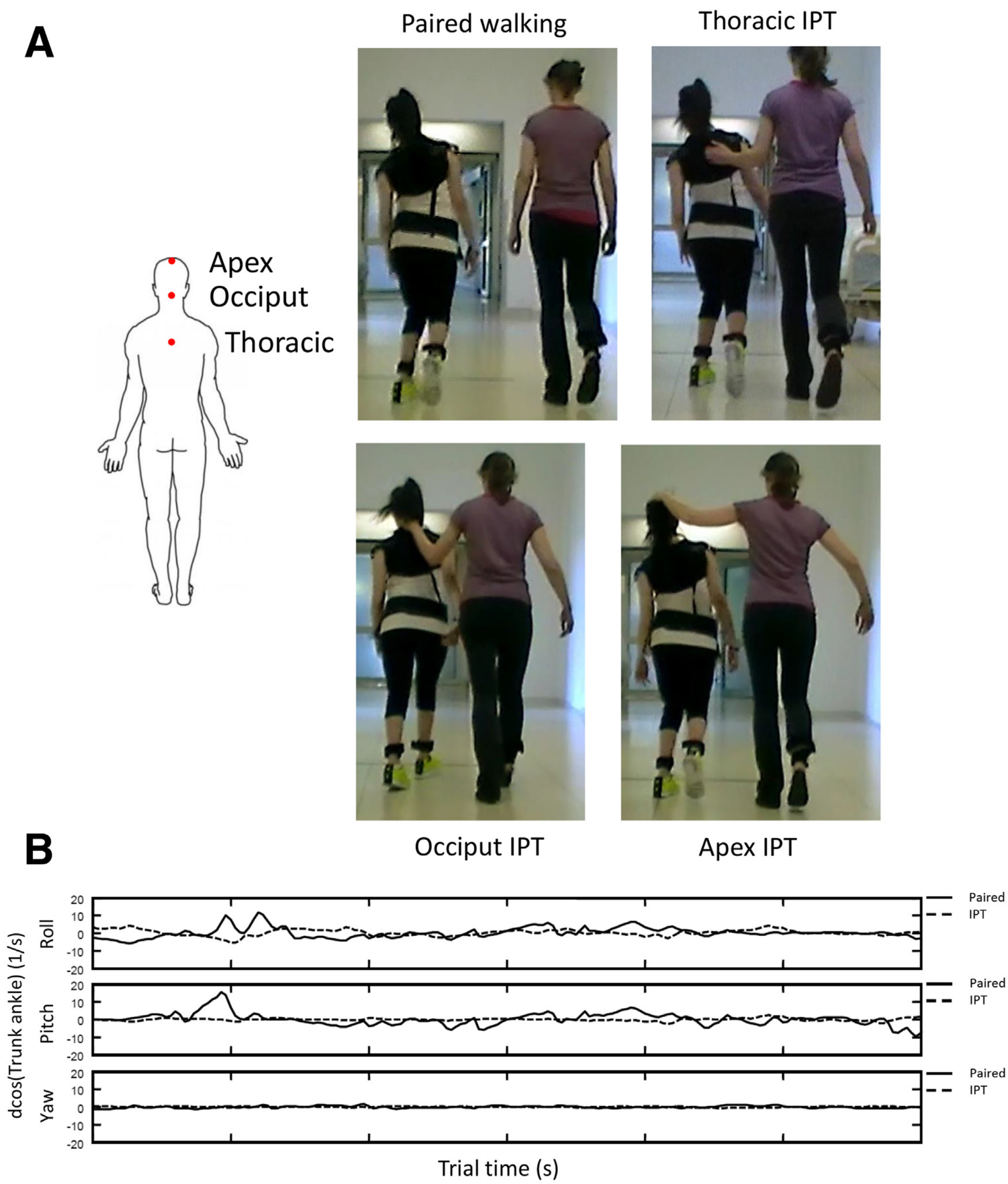

Fig 1 (A) Four of the 5 testing conditions demonstrated on an individual with CP (left) by a therapist (right). Deliberately light IPT was provided to 3 contact locations: thoracic, occiput, and apex (experimental conditions; control condition: paired walking). The individual with CP is wearing trunk and pelvis parts of an inertial measurement unit sensor suit (not a thoracolumbosacral orthosis). (B) Illustrative inertial measurement unit sensor traces of a single CP participant. The 3 panels show transformed trunk angular velocity around a sensor's roll, pitch, and yaw axes for paired walking (straight line) and thoracic IPT (dashed line). To prevent angular flip-overs between $-180°$ and $180°$ from distorting the variability measure, sensor orientation angles were cosine-transformed before differentiation ($\cos(\alpha)/s$). Abbreviation: dcos, differentiated cosine.

Although our results did not exactly turn out as hypothesized, our study yielded some interesting findings. The participants with CP showed less HVS with apex and occiput IPT in contrast to thoracic IPT. Numerically, these 2 conditions tended to differ from the 2 control conditions (walking alone, paired walking) in opposite directions, with reduced HVS during apex IPT. Nevertheless, it shows that the location at which IPT is applied to the receiver's body does matter in CP. In contrast, the TD group showed the lowest HVS in occiput and apex IPT compared with both walking alone and paired walking. Further, while the CP group did not walk with measurably changed speed, the TD group walked with reduced speed by taking shorter average steps in the IPT conditions.

We assumed that IPT at the head facilitates the role of the head as an inertial guidance platform for locomotion, improves control of trunk sway, and optimizes gait in CP. In this respect, only the TD group behaved in correspondence with our expectations. The TD group showed the least HVS in both head contact conditions

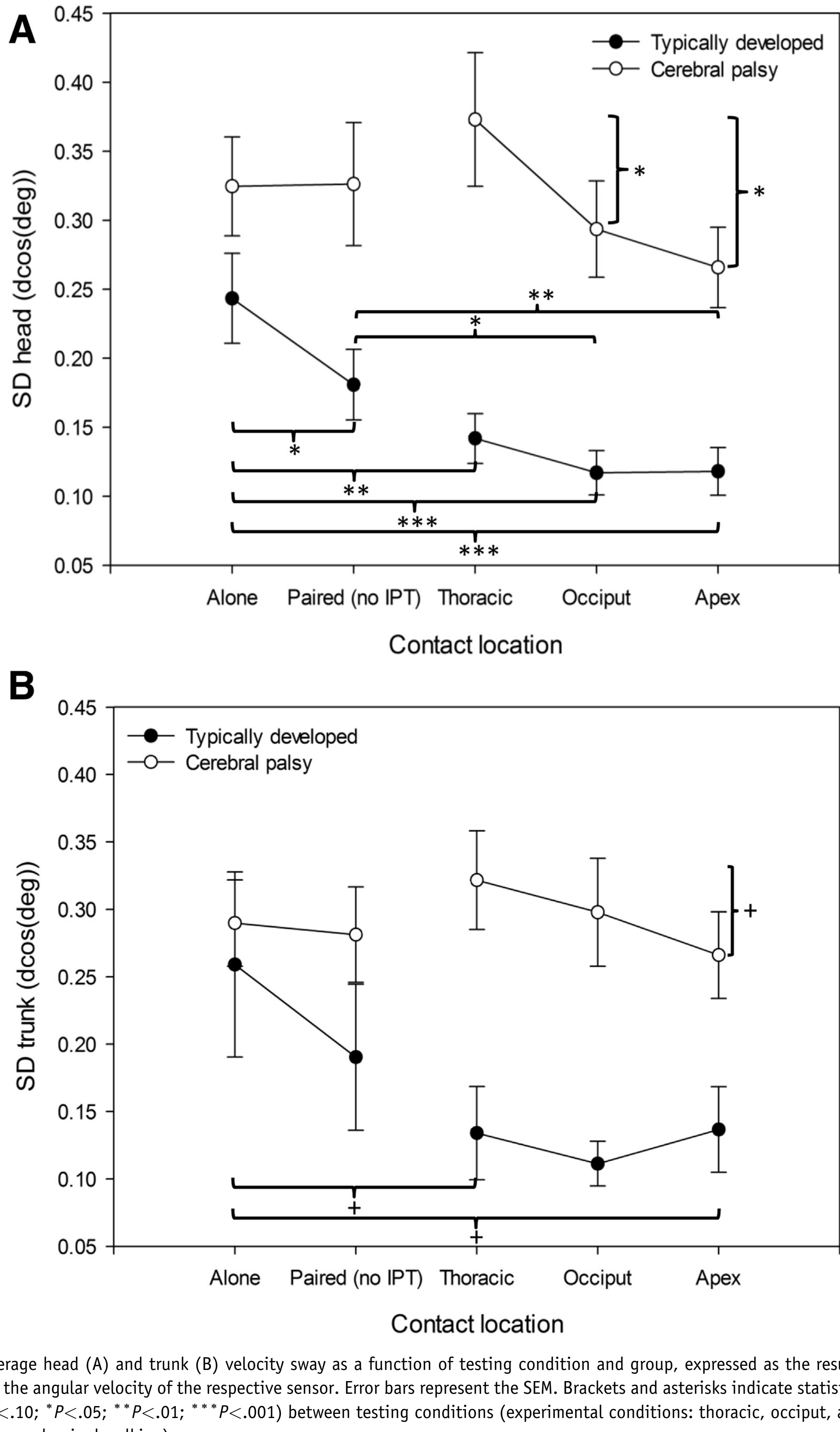

Fig 2 The average head (A) and trunk (B) velocity sway as a function of testing condition and group, expressed as the resultant, direction-unspecific SD of the angular velocity of the respective sensor. Error bars represent the SEM. Brackets and asterisks indicate statistically significant differences ($^{+}P<.10$; $^{*}P<.05$; $^{**}P<.01$; $^{***}P<.001$) between testing conditions (experimental conditions: thoracic, occiput, and apex; control conditions: alone and paired walking).

and a small corresponding reduction in TVS. This indicates that the control of head sway became more influenced by a headcentric sensory signal compared with thoracic IPT or walking without IPT.

The CP group did not demonstrate any effect of the presence of the physical therapist/conductor. In contrast, the TD participants reduced HVS during paired walking, which may be the result of some form of "social facilitation," perhaps by some form of spontaneous interpersonal entrainment of the stepping pattern between the physical therapist/conductor and participant. The difference between the groups could mean that the CP group was insensitive to or unable to comply with the social demands and constraints of interpersonal coordination.

With respect to human ontogenetic locomotor development, it was proposed that selective control of the neck's movement degrees of freedom is a key feature of a mature upper body gait pattern.[19] Wallard et al[20] observed an "en bloc" head-on-trunk strategy with increased head angle variability in the frontal plane during walking in children with CP, and proposed that it might express an "en bloc" compensatory strategy by deliberate reduction of the neck's movement degrees of freedom. Because we found subtle effects of apex IPT in the CP group, we speculate that apex IPT may still be a therapeutic approach to open up a habitual "en bloc" strategy and to enable the exploration of neck articulation as well as the benefits of actively stabilized head orientation. Advocates of a "hands-off" approach[21] emphasize unrestricted self-exploration of the movement repertoire by the patient. We perceive deliberately light IPT as a married form between "hands-on" and "hands-off" because of the low contact forces involved and the absence of active restriction. The "guidance" in IPT is considered less physical but more implicit to the social context.

We did not find any differences between symptom subgroups among the participants with CP, which indicated that differences in symptoms did not alter the susceptibility to IPT and its social context. Visual inspection of our data showed that the responsiveness of the individuals with CP showed a high degree of interindividual variability. Since only 2 IPT providers were involved in data collection, it is unlikely that variability in the way IPT was applied caused this. Instead, factors within the individuals with CP must be the reason—for example, current motor competence in the control of trunk sway and neck articulation. The observation that more impaired individuals with CP, as indicated by their GMFCS level, performed worse was to be expected. It shows, however, that the capacity to respond to IPT is not determined by the general impairment level.

Study limitations

It might appear as a limitation, that the sway variability measures used in our study do not represent positional variability. Variability of angular velocity, however, is more closely related to the control of body balance during locomotion. Differentiation of a signal acts as a high-pass filter, which removes low-frequency drift, which could occur in the absence of any positional control. For example, Allum and Carpenter[22] recommended measurements of trunk angular velocity as a means to differentiate between specific control deficits of body balance.

We did not restrict our recruitment to participants with CP showing specific symptoms, although this could have made our results more generalizable for this symptom subgroup. Our intention was to evaluate the general feasibility of IPT in a wide spectrum of symptoms. The present study aimed to advance the understanding of the "mechanisms of action" of IPT for balance support during walking in individuals with CP, and thus was designed as a single-session, proof-of-concept study. The long-term benefits of deliberately light IPT during locomotor training in CP remain speculative at this point and therefore require a properly designed multisession intervention study.

Conclusions

Deliberately light interpersonal contact applied to the apex of the head results in a reduction of HVS compared with thoracic IPT during walking in children and adolescents with CP, irrespective of their symptoms. This implies that the effect of IPT depends on the location at which it is applied in individuals with CP. The CP group, however, did not act in the same way as the TD group. TD individuals were much more responsive in terms of reductions in HVS because of the presence of the therapist and the application of IPT. The difference may be an expression of reduced sensitivity regarding the social affordances of the IPT situation in individuals with CP, which could indicate a restriction of the ability to adapt behavior to external social conditions. Further research is still required to assess any longer-term benefits of IPT in individuals with CP.

Suppliers

a. Xsens MTw; Xsens Technologies BV.
b. Matlab (2014a); MathWorks, Inc.
c. IBM SPSS statistics 23; IBM Corp.

Keywords

Cerebral palsy; Locomotion; Postural balance; Rehabilitation; Therapeutic touch

Corresponding author

Leif Johannsen, PhD, School of Health Sciences, Faculty of Medicine and Health Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, United Kingdom. *E-mail address:* L.Johannsen@uea.ac.uk.

References

1. dos Santos AN, Pavao SL, de Campos AC, Rocha NA. International Classification of Functioning, Disability and Health in children with cerebral palsy. Disabil Rehabil 2012;34:1053-8.
2. Kavanagh JJ, Barrett RS, Morrison S. Upper body accelerations during walking in healthy young and elderly men. Gait Posture 2004;20:291-8.
3. Schweizer K, Brunner R, Romkes J. Upper body movements in children with hemiplegic cerebral palsy walking with and without an ankle-foot orthosis. Clinical Biomech (Bristol, Avon) 2014;29:387-94.
4. Heyrman L, Feys H, Molenaers G, et al. Altered trunk movements during gait in children with spastic diplegia: compensatory or underlying trunk control deficit? Res Dev Disabil 2014;35:2044-52.

5. Attias M, Bonnefoy-Mazure A, Lempereur M, Lascombes P, De Coulon G, Armand S. Trunk movements during gait in cerebral palsy. Clinical Biomech (Bristol, Avon) 2015;30:28-32.
6. Heyrman L, Desloovere K, Molenaers G, et al. Clinical characteristics of impaired trunk control in children with spastic cerebral palsy. Res Dev Disabil 2013;34:327-34.
7. Cromwell R, Schurter J, Shelton S, Vora S. Head stabilization strategies in the sagittal plane during locomotor tasks. Physiother Res Int 2004;9:33-42.
8. Pozzo T, Berthoz A, Lefort L, Vitte E. Head stabilization during various locomotor tasks in humans. II. Patients with bilateral peripheral vestibular deficits. Exp Brain Res 1991;85:208-17.
9. Horak FB, Macpherson JM. Postural orientation and equilibrium. In: Rowell LB, Shepherd JT, editors. Handbook of physiology. Section 12. Exercise: regulation and integration of multiple systems. New York: Oxford University Pr; 1996. p 255-92.
10. Pavão SL, Silva FP, Savelsbergh GJ, Rocha NA. Use of sensory information during postural control in children with cerebral palsy: systematic review. J Mot Behav 2015;47:291-301.
11. Baldan AM, Alouche SR, Araujo IM, Freitas SM. Effect of light touch on postural sway in individuals with balance problems: a systematic review. Gait Posture 2014;40:1-10.
12. Johannsen L, Wing AM, Hatzitaki V. Contrasting effects of finger and shoulder interpersonal light touch on standing balance. J Neurophysiol 2012;107:216-25.
13. Sofianidis G, Hatzitaki V, Grouios G, Johannsen L, Wing A. Somatosensory driven interpersonal synchrony during rhythmic sway. Hum Mov Sci 2012;31:553-66.
14. Johannsen L, McKenzie E, Brown M, Redfern MS, Wing AM. Deliberately light interpersonal touch as an aid to balance control in neurologic conditions. Rehabil Nurs. 2014 Dec 7. [Epub ahead of print].
15. Krishnamoorthy V, Slijper H, Latash ML. Effects of different types of light touch on postural sway. Exp Brain Res 2002;147:71-9.
16. Rogers MW, Wardman DL, Lord SR, Fitzpatrick RC. Passive tactile sensory input improves stability during standing. Exp Brain Res 2001; 136:514-22.
17. Mergner T, Maurer C, Peterka RJ. A multisensory posture control model of human upright stance. Prog Brain Res 2003;142:189-201.
18. Palisano RJ, Hanna SE, Rosenbaum PL, et al. Validation of a model of gross motor function for children with cerebral palsy. Phys Ther 2000; 80:974-85.
19. Ledebt A, Bril B, Wiener-Vacher S. Trunk and head stabilization during the first months of independent walking. Neuroreport 1995;6: 1737-40.
20. Wallard L, Bril B, Dietrich G, Kerlirzin Y, Bredin J. The role of head stabilization in locomotion in children with cerebral palsy. Ann Phys Rehabil Med 2012;55:590-600.
21. Dirks T, Blauw-Hospers CH, Hulshof LJ, Hadders-Algra M. Differences between the family-centered “COPCA” program and traditional infant physical therapy based on neurodevelopmental treatment principles. Phys Ther 2011;91:1303-22.
22. Allum JH, Carpenter MG. A speedy solution for balance and gait analysis: angular velocity measured at the centre of body mass. Curr Opin Neurol 2005;18:15-21.