HAZARI, A., AGOURIS, I., WAKODE, P.S., JADHAV, R.A., SHARMA, N., JENA, S. and SHARMA, M. 2019. Head and trunk kinematics and kinetics in normal and cerebral palsy gait: a systematic review. *European journal of physiotherapy* [online], Latest Articles. Available from: https://doi.org/10.1080/21679169.2019.1573919

Head and trunk kinematics and kinetics in normal and cerebral palsy gait: a systematic review.

HAZARI, A., AGOURIS, I., WAKODE, P.S., JADHAV, R.A., SHARMA, N., JENA, S. and SHARMA, M.

2019

Head and trunk kinematics and kinetics in normal and cerebral palsy gait: a systematic review

Left Running Head: A. HAZARI ET AL.

Right Running Head: BIOMECHANICAL CHANGES IN CEREBRAL PALSY GAIT

Animesh Hazari [1] * Ioannis Agouris [2] Pallavi S. Wakode [3] Radhika A. Jadhav [3] Namrata Sharma [1] Sonali Jena [1] Mahesh Sharma [1]

[1]Lovely Professional University, Phagwara, India;
[2]Robert Gordon University, Scotland, UK;
[3]Manipal University, Manipal, India

**CONTACT Animesh Hazari animesh.23443@lpu.co.in Lovely Professional University, Phagwara 144411, Punjab, India*

ABSTRACT

Background: Cerebral palsy (CP) is a neuromuscular disability characterised by a persistent disorder of movement and posture due to a non-progressive lesion in a developing brain. In children with CP, gait is compromised in a variety of ways. A number of studies have suggested that there is a higher degree of biomechanical variations including kinematics and kinetics at head and trunk while analysing a CP gait. Since coordinated movements of head and trunk are important to analyse a typical gait, it is important to determine these biomechanical changes among children with CP for altered movements such as decreased head and trunk stability. Studies have also reported a variety of outcome measures for clinical use. However, the results among the studies are not consistent as there is variability for altered biomechanics based on type and level of the disorder which requires further investigation. Although clinically very useful, the data regarding the head and trunk biomechanics in children with CP is limited. In this study, a systematic review was done to determine the head and trunk kinematic and kinetics variations in CP gait compared to TD children of the same age-group.

Methodology: Scientific articles were obtained by a search in databases including Science Direct, Cinahl, Springer Link, Sport discuss, Web of Science and Pubmed. Limitations used were AND/OR. Full-text articles from 1999 to 2017 in English were selected.

Results: A total of 3029 records were identified that included Science Direct (*n* = 1854), Cinahl (*n* = 176), Springer Link (*n* = 121), Sports Discuss (*n* = 101), Web of Science (*n* = 14) and Pubmed (*n* = 763). After removing the duplicates, 1786 records were obtained. Fifty-one full text articles were selected for the eligibility and 27 were included in the study.

Conclusions: In this review study, we conclude that children with CP have a significant difference in head and trunk kinetics and kinematics compared to age-matched TD children

KEYWORDS Cerebral palsy; typical gait; stability; unstable gait; trunk movements; head movements; compensatory movements; kinetics/kinematics, gait biomechanics.

Introduction

Gait is crucial to attain functional independence in daily life. Typical human gait is comprised of reciprocal limb movements to advance the body while simultaneously maintaining stance stability [1]. The oscillations of the upper body during level walking are characterised by an attenuation of the linear acceleration going up from pelvis to head level. This is a control strategy used to compensate for perturbations generated by the lower body movements to preserve the head stability, and hence, improve walking balance [2]. However, in children with cerebral palsy (CP), gait is compromised in a variety of ways due to a non-progressive lesion in a developing brain [3]. Children with CP show altered movements such as decreased head and trunk stability [4]. Typical gait comprises the movements of various body segments but gait in a developing CP child is a complex process [5].

As walking is a basic requirement for many daily activities, biomechanical gait analysis provides important information on the functional capacity of the subjects. Biomechanical analysis could reveal the organisational and motor strategies used by the central nervous system to minimise the destabilising translation of the trunk during gait [6]. Studies have shown that children with CP develop a postural strategy in which the head and trunk move as a single segment, causing the whole body to swing from left to right [7]. These variables show the presence of a particularly pronounced head roll for these children, a compensatory strategy in gait by reducing the number of degrees of freedom to control their body in space [8].

In clinical practice; gait is analysed either visually or by using questionnaires. Whereas, in research settings, advanced motion analysis systems are used to carry out quantitative clinical gait analysis (CGA) and evaluate the impact of age, gender and several pathologies on gait characteristics [9]. The use of different technologies such as an optoelectronic system (VICON, QUALYSIS, MOTION ANALYSIS, CODA MOTION, BTS etc.) synchronised with force plates (AMTI, KISTLER, etc.) and with electromyography (EMG) system has been very useful. The advancement in the instrumentation and use of three dimensional motion analyses has also added to a higher degree of precision and accuracy for kinematic analysis of gait variables like joint angles, postural changes, velocity, acceleration, etc. In addition, the force platform has been very informative in quantifying in the external and internal force like ground reaction force, internal/external moment and muscles force, respectively. Apart from this, the electric activity of the muscle and muscular force could be determined by using EMG devices. An EMG analysis could be very useful in determining both quality and quantity of muscle recruitment and their activity, thereby understanding of compensatory gait patterns.

Need for the review

Based on the information obtained during clinical evaluation and gait analysis examinations, various corrective treatments could be proposed to control and improve the efficiency of pathological gaits seen in patients with CP [10]. Therefore, it is extremely important to understand and establish the foundation of biomechanical analysis of head and trunk during CP gait. The studies from the previous literature suggest that children with CP demonstrate different strategies to maintain head, neck and trunk balance in space both in static and dynamic phases of gait cycle. However, the biomechanical changes and compensation may differ in quantity and quality individually depending upon the type and level of the disorder. In order to understand these aspects, the kinematic and kinetic analysis of the CP gait could be important. Study reports based on visual observations indicate that CP children often show decreased head and trunk stability but the clinical reasoning, justification, quality and quantity of movement are lacking on observational analysis. This could be addressed by studying biomechanical deviations using motion analysis systems. Also, there is a dearth in literature regarding the kinematic and kinetic analysis of head and trunk deviation [11]; and it could be very useful to study these changes for better understanding of the CP gait characteristics by conducting a review study. Therefore, in order of study the kinematic and kinetic changes at head and trunk and compile the information from the previous literature, this study aims to perform a systematic review. This could be also useful to understand the compensatory strategies used by children with CP compared to typically developing (TD) children of the same age group. Since the findings from the previous study suggest a higher degree of variability in biomechanical alteration of CP gait, this review study could be clinically important because the movement of head and trunk in CP is essential in the comprehension of the CP gait and possible stabilising movements to help the pathological gait. The use of more objective methods, such as 3-dimensional movement analysis could contribute to gain further insights in trunk and head involvement during gait in children with CP [12]. These findings could also be helpful design appropriate therapeutic strategies.

Methods

Search strategy

Scientific articles were obtained by a search in databases including Science Direct, Cinahl, Springer Link, Sport discuss, Web of Science and Pubmed.

The search was performed by using following keywords in combination: 'Cerebral palsy' 'Typical Gait', 'stability', 'unstable gait', 'Trunk movements', 'Head movements', 'compensatory movements', 'Kinetics/Kinematics' and 'Gait Biomechanics'. For example, the search strategy in Pub med with keywords has been given below using the advanced search engine and builder:

(((((((('cerebral palsy'[MeSH Terms] OR ('cerebral'[All Fields] AND 'palsy'[All Fields]) OR 'cerebral palsy'[All Fields]) AND (('cerebral palsy'[MeSH Terms] OR ('cerebral'[All Fields] AND 'palsy'[All Fields]) OR 'cerebral palsy'[All Fields]) AND ('gait'[MeSH Terms] OR 'gait'[All Fields]) AND Biomechanics[All Fields])) AND ('kinetics' [MeSH Terms] OR 'kinetics'[All Fields])) OR (('biomechanical phenomena'[MeSH Terms] OR ('biomechanical' [All Fields] AND 'phenomena'[All Fields]) OR 'biomechanical phenomena'[All Fields] OR 'kinematics'[All Fields]) AND ('head movements'[MeSH Terms] OR ('head'[All Fields] AND 'movements'[All Fields]) OR 'head movements'[All Fields]))) AND (('torso'[MeSH Terms] OR 'torso'[All Fields] OR 'trunk'[All Fields]) AND ('movement'[MeSH Terms] OR 'movement'[All Fields] OR 'movements'[All Fields]))) AND (Typical[All Fields] AND ('gait'[MeSH Terms] OR 'gait'[All Fields]))) OR ('gait'[MeSH Terms] OR 'gait'[All Fields])) AND (Compensatory [All Fields] AND ('gait'"[MeSH Terms] OR 'gait'[All Fields])).

Limitations used were AND/OR. Articles from 1999 to 2018 were selected. Full-text articles in the English language were selected.

Studies selection process and criteria

The papers were pre-selected by reading the titles and abstracts by three authors. The selection was completed after reading the full texts. The risk bias in individual study was handled by obtaining a consensus between the reviewers based on the inclusion/exclusion criteria as given below (Table 1). The quality of the studies was also assessed following which the final selection of the studies was done.

Table 1. Inclusion and exclusion criteria for reviewed studies.Table Layout

Inclusion criteria	Exclusion criteria
– Studies on head and trunk movement of cerebral palsy gait – Studies comparing gait of normal or typically developing children with age-matched cerebral palsy children – Biomechanical analysis of head and trunk – Outcome measures of interest – A) 2/3-dimensional kinematics and kinetics variables of head and trunk movement B) Electromyography of head and neck muscles while walking including kinematic and kinetic analysis of head and trunk C) Visual analysis of gait and clinical tools with a focus on head and trunk kinetics and kinematics	– Studies with biomechanical analysis other than head and trunk – Studies that did not report at least one outcome variable of interest – Studies that reported subjects with other associated neurological disorders – Studies without a comprehensive methodology

Study quality assessment: The quality of the review studies were assessed by three blinded assessors. The Down and Black scoring system was used and a score of ≥7 was considered as a good quality. A consensus was obtained from all assessors before finalising the studies for the review.

Results

A total of 3029 records were identified that included Science Direct (n = 1854), Cinahl (n = 176), Springer Link (n = 121), Sports Discuss (n = 101), Web of Science (n = 14) and Pubmed (n = 763). Additional nine records were identified from the university repository and textbooks. After removing the duplicates, 1786 records were obtained. Then, 215 studies were removed at this stage which included text book, thesis and unpublished studies. This was followed by the title and abstract screening for a total of 1571 studies from which 1520 records were excluded for inappropriate title and abstract matching to the desired review study. Therefore, a total of 51 full text articles were finally collected for review. Twenty-five (n = 25) records were further excluded as full text were not available (n = 3), methodology not appropriate (n = 6), language other than English (n = 2) did not match the inclusion and exclusion criteria (n = 11), comparison of CP population between the variants of the same disorder instead of TD children (n = 3). Finally, 27 full text articles in English language were selected for the review. The selection process and records have been diagrammatically shown in Figure 1. The selected articles with characteristics findings have been shown in Tables 2 and 3.

Figure 1. Outlines the process and search results from an extensive literature search.

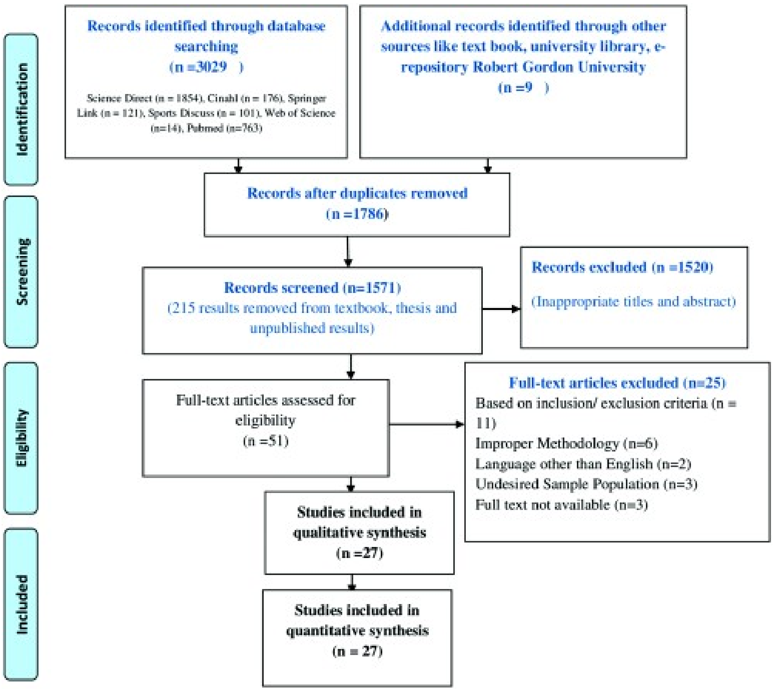

Table 2. Studies description.Table Layout

References	Year	Study design	Population				
			Sample size	CP	Typical	Age (years)	GMFC's
[13]	2018	Cross-sectional	52	30	22	9.1–11.7	1–3
[14]	2017	Cross-sectional	72	52	20	8.5–14.5	1–2
[15]	2016	Cross-sectional	52	30	22	9.1–11.7	1–3
[16]	2016	Cross-sectional	40	20	20	2–9	1–3
[4]	2016	Cross-sectional	50	26	24	4–12	–
17]	2014	Cross-sectional	36	16	20	8–14	–
[18]	2014	Cross-sectional	40	23	17	8–18	–
[19]	2014	Cross-sectional	34	17	17	5–18	1–3
[20]	2014	Cross-sectional	114	92	22	0–25	1–3
[6]	2014	Cross-sectional	32	16	16	9–13	1–2
[21]	2014	Cross-sectional	70	41	29	5–18	1–3
[22]	2014	Cross-sectional	107	92	15	5–30	1–3
[23]	2014	Cross-sectional	20	20	0	5–15	1–2
[24]	2013	Cross-sectional	100	100	0	8–15	1–3
[12]	2013	Cross-sectional	40	20	20	2–10	1–2
[25]	2011	Cross-sectional	56	26	30	8–15	1–3
[26]	2013	Cross-sectional	48	31	17	11–26	1–2
[27]	2013	Cross-sectional	149	122	27	17–23	1–3

References	Year	Study design	Population				
			Sample size	CP	Typical	Age (years)	GMFC's
[6]	2012	Cross-sectional	32	16	16	9–13	–
[28]	2012	Cross-sectional	399	375	24	–	1–3
[29]	2011	Cross-sectional	34	17	17	2–8	1–2
[30]	2010	Cross-sectional	34	18	16	7 & above	1–2
[31]	2009a	Cross-sectional	26	16	10	8–14	–
[32]	2009b	Cross-sectional	42	32	10	8–14	–
[33]	2008	Cross-sectional	33	33	–	4–14	1–4
[34]	2007	Cross-sectional	19	10	9	8–18	–
[35]	1999	Cross-sectional	12	6	6	7–12	–

Table 3. Description of activity, assessment tools and variables.Table Layout

References	Activity	Assessment tools	Outcome variables
[13]	Bare foot walking towards a target, 20-cm tall of 10 cm diameter, and 3 m away on the floor	Three-dimensional, eight camera, motion analysis system (Vicon MX40VR, Oxford, UK) with a sampling rate of 100 Hz using 34 retro reflective full body marker system	Transverse plane movement: mean head rotation (HTPM) and mean trunk rotation (TTPM) Sagittal plane movement: mean head flexion (HSPM) and mean trunk flexion (TSPM)
[14]	Unassisted walking with self-selected speed	CODA cx1 system (Charnwood Dynamics Ltd, Leicestershire, UK)	Measurement of lumbar segment with respect to pelvic. In sagittal plane, lumbar flexion, in coronal plane lumbar side flexion, in transverse plane lumbar rotation
[13]	Barefoot walking towards a 15 cm diameter lamp (Red) for 12-m walkway (Gaze target), and return to the starting point (No target).	Three dimensional, 8-camera motion analysis system (Vicon MX40, Oxford, UK) with a full-body biomechanical model. The lower body was analysed according to the Newington Model and the upper body according to the Plug-In-Gait model (Vicon).	Temporal-spatial parameters including cadence, walking velocity, step length, single- and double-support times Kinematics of head, neck and trunk
[16]	10-m walk	Magneto-inertial measurement unit (Opal, APDM Inc., Portland, OR)	3D acceleration, angular velocity, magnetic field vector for head attenuation
[4]	10 m self –selected speed with no restricted arm swing	Vicon system with eight camera	Trunk sways amplitude, velocity and acceleration Trunk rotation velocity amplitude and acceleration
[17]	Walking barefoot at self-selected speed along a 10-m walkway	Optoelectronic system with passive markers (ELITE2002, BTS, Milan, Italy) 2 force platforms (Kistler AG, Winterthur, Switzerland)	Upper Limb Kinematics
[18]	Walking barefoot at a self-selected speed on a 10 m level ground walkway.	VICON motion analysis system with twelve cameras	Thorax, spine and pelvic range of motion
[19]	10-m walk	Codamotion cx1 system (Charnwood, Dynamics, Leicestershire, UK)	Sagittal inclination, mediolateral inclination, peak separation, gait profile score
[20]	10-m walk	Viconn motion system (Vicon Peak, Oxford, UK) with twelve-camera	Walking speed, thorax, and spine angle in transverse, sagittal and coronal plane

References	Activity	Assessment tools	Outcome variables
[6]	Walking 10-m walkway	3D gait analysis system, Force platform analysis	Kinetic data between COM and COP and propulsive forces around AP and ML axis, Spatiotemporal parameters
[21]	5-m walkway	Trunk accelerometers- a six-degrees-of-freedom inertial sensor (MTx. Xsens, Enschede, Netherlands)	Trunk acceleration, inter-stride regularity, and asymmetry of accelerations in Anterior-posterior, Medio-lateral, and Vertical directions.
[22]	Barefoot walking at a self-selected speed along a 12-m walkway	(VICON Mx3+; ViconPeak1, Oxford, UK) with 12 cameras	Thorax Kinematics
[23]	10-m walkway	Head and Trunk- custom-made trunk model based on 3D movement analysis Lower limb-VICON with 15 camera	Range of motion The gait profile score (GPS) Trunk profile score (TPS) Gait variable scores (GVSs) Trunk variable scores (TVSs)
[24]	Walking 10-m walkway	3D gait analysis system Trunk profile score (TPS), Trunk variable score (TVS)	Absolute and relative angles for head, thorax and pelvis, Spatiotemporal parameters
[12]	Walking 10-m walkway	3 D Kinematic gait analysis system	3D Rotations, the angle of Kyphosis, the angle of Lordosis.
[25]	Walking 10 m walkway	3D kinematic gait analysis system	Upper and lower body kinematics and angular velocity, angle of trunk and pelvis
[26]	Walking 10-m walkway	(ViconPeak1, Oxford, UK) and Matlab 2012a (MathWork, Natick, MA).	Angular displacement of the pelvis, hip, knee and ankle joints
[27]	Walking 10-m walkway	VICON optoelectronic movement capture system with eight infra-red cameras at 200 Hz.	Angular displacement of Head and Trunk in sagittal and frontal plane
[6]	Barefoot walking over a 10-m walkway at self-selected speed	VICON Motion Systems, Oxford Metrics, UK using 8 camera	Relative and absolute Range of Motion for head, thorax, pelvis, shoulder line and spine
[28]	Walking 7-m walkway	3D gait analysis system, Force platform analysis, MRC scale	Trunk and hip kinematics and kinetics
[29]	Walking 10-m walkway	Inertial sensor device (FreeSense1, Sensorizes.r.l., Rome)	Anterior-posterior acceleration Lateral-lateral acceleration Cranio-caudal acceleration
[30]	Walking 10-m walkway	Anthropometry, Electromyographic analysis	Electromyographic activity of trunk and lower limb muscles
[31]	Barefoot walking at self-selected speeds on a 6-m walkway	eight-camera Eagle Motion Analysis System (Motion Analysis Corp, Rohnert Park, CA)	Peak-to-Peak magnitude of COM and COP displacement
[32]	Walking	Force plate signal analysis	Velocity of acceleration of COM and COP, walking speed, stride duration
[33]	Walking 10-m walkway	BodyBuilder software (Vicon Peak, 14 Minns Business Park, West Way, Oxford OX2 0JB, UK).	spatiotemporal parameters, kinematic parameters for pelvis
[34]	Walking 10-m walkway	3D kinematic gait analysis system	Gait parameters in sagittal and frontal plane

References	Activity	Assessment tools	Outcome variables
[35]	Treadmill walking at preferred speed	2D Peak Performance Motion analysis system	Vertical head velocity and displacement

Discussion

From this review study, we found that the kinematic and kinetic analysis of head and trunk movement among CP children was an important outcome measure for clinical purpose. There was a major deviation in head and trunk movement with compensation compared to TD children gait. Since the findings from the previous studies could be very informative in understanding the gait characteristics of CP children; this systematic review could be valuable for discussion under the following sub-headings.

Study design, sample size and recruitment details

In our review, we found that all the studies were observational (cross-sectional). Based on our review, it could be suggested that studies with randomised control design would be more helpful in the clinical understanding of gait characteristics for individual rehabilitation rather than just acknowledging the ailments associated with a larger population by cross-sectional study design. Due to the developmental changes that occur in children as they grow, longitudinal studies are needed to identify the relationship between age and postural control and its impact on gait. Most of the studies compared CP children with age-matched TD children [4,6,7,12,14–22,27–32,34,35] except two studies did not have TD as a comparable group [11,33]. Considering age-matched TD children in the gait analysis could provide accurate and effective measures of comparison regarding functional capacity and postural deviation from the baseline. The comparison with TD children could also be used to understand the major head and trunk compensatory strategies used by CP children. For example, the study done by Wallard et al. [7] suggested that children with CP develop and `en bloc strategy to move head and truck as a single unit.

In few studies, distribution of participants could also be seen based on CP classification [4,16,20,23–25,27,31]. The most common type of CP under inclusion criteria of the review studies was spastic hemiplegia or diplegia. Only two studies included participants with either hemiplegia or diplegia [4,17]. In addition, some authors compared two different types of CP viz. spastic diplegia (SD) with hereditary spastic paraplegia (HSP) which could establish the marginal difference in gait characteristics between the two comparable groups. The study done by Bonnefoy-mazure [26] in this regard could be very useful. The study suggested that participants with HSP showed more trunk and spine movements to compensate for lower limb movement disorder whereas SD children used arm movements significantly. This finding could be a useful clinical sign to differentiate a HSP from SD.

In our review, we found that majority of the studies had smaller sample size except for few studies that studied over 100 participants and clinical analysis [20,22,24,27]. A smaller sample in the majority of the studies suggested that it is difficult to obtain more participants from this population group due to (a) specific inclusion and exclusion criteria (b) different degrees of functional impairment and (c) patient compliance. Also, CP could be a relatively risky population to study upon and obtain consent. The study done by Attias et al. [20] performed 141 CGA and suggested that thorax movement plays an important role in CP gait. In CP children, there was a higher range of motion (ROM) in thorax and spine with more impairment seen at higher level of thorax ROM. However, a more sample size could be useful to strengthen the findings of the study both clinically and statistically. From the review findings, based on smaller sample size, it is difficult to comment and propose a minimal clinical significant difference on head and trunk kinematic and kinetic deviations for CP children. Nevertheless, a significant head and trunk movement alterations have been reported by most of the studies among CP children compared to TD children.

The participants were assessed for their functional capacity and categorised according to Gross Motor Function Classification System (GMFCS). Six studies included participants with a GMFCS score of I-II [7,12,14,23,27,29] whereas nine authors categorised their participants under GMFCS score of I–III [13,15,16,19–22,24,25,28,30]. However, nine studies did not use GMFCS for functional classification and categorisation of the studied sample population [4,6,11,17,18,31,32,34,35]. From this review, we could suggest that in CGA categorisation of CP children on GMFCS scale could be important to determine the differences in the impairments based on the level and severity of the disorders. The study done by Attias et al. [20] concluded that diplegic CP with GMFCS level III demonstrated higher range of spinal and thorax motion from the mean compared to GMFCS level II and I, respectively. Similarly, the study done by Heyrman et al. [12] concluded that head and trunk movement impairments were multidimensional in more disabled GMFCS II children. Also, the lateral bending movement of thorax in CP increased with increased level of GMFCS. In a recent study conducted by Bartonek et al. [13] which studied the head and trunk movement in CP with and without a visual target suggested no effect of visual target on head, trunk and neck movement in CP children. However, they found that compared to CP with GMFCS level I–II and TD children, CP children with GMFCS III (CP 3) showed higher significant changes for head sagittal plane, trunk sagittal plane, trunk frontal plane, trunk transverse plane and neck transverse plane movements for both visual target and no visual target condition. The study done by Heyrman et al. [24] concluded that spastic CP children show impaired trunk movement based on topography and severity of motor impairments as reflected by GMFCS levels. This clearly suggests that the level of impairment adds to the degree of biomechanical alteration and compensation in CP children.

The inclusion and exclusion criteria for the majority of the studies were similar. The ambulatory functional capacity under inclusion criteria was 10 m in most of the study except one study that insisted ambulatory function of minimum 60 m [7]. As there is high variability of clinical features in CP, classifying the children into different topographical classification would give a better view of their functional capacity and impairments. Regarding recruitment source and strategy, it could be suggested that many studies failed to report this information. Three authors reported hospital outpatient clinic as the recruitment source [19,21,35] whereas other five authors found their participants from the university and hospital laboratory database [12,13,15,22,29].

Instrumentation and motion analysis system

In our review, we found that the most common motion analysis tool used for kinematics was VICON motion analysis system [4,13,15,18,20,22,23,26,33] whereas for kinetics force platform was common in practice [7,28]. The details on motion analysis system could be seen from Table 3. For instance, the study done by Bartonek et al. [13,15] used VICON MX40, Oxford UK with eight cameras at a frequency of 100 Hz. A full body biomechanical model (Plug-In-Gait) with 34 retro-reflective markers was used on bony landmarks including head, trunk, pelvis and lower limb under the Newington model. Helen Hayes marker model could be used as the standardised position of markers. Three dimensional motion analyses was commonly used, however, the study conducted by Holt et al. [35] used two dimensional systems. It could be said that with advancement in motion analysis system, the current state of art requires 3D motion for better accuracy of results. Apart from this, there were few studies which used motion analysis system other than Vicon [7,13–15,19,23,25,]. As it is important to give a better idea of movements of different body segments, retro-reflective markers were used in many studies, but marker placement and models varied between the studies and could be a source of differences in the results. The study conducted by Galli et al. [17] used optoelectronic systems with passive markers for kinematic data. The use of passive markers could be source of artefact between the studies and a standardised method should be used. Some author also used inertial sensor device and trunk accelerometers respectively [21,29]. But these tools are costly and needs a well-equipped laboratory to carry out the study. It would also require a well-trained assessor. Thus, a cost-effective tool could be suggested for use in clinical practice. In this review, only one study investigated the muscle activities of the trunk and lower limb using EMG [30]. Our review suggested that kinematic and kinetic measurement should be accompanied by an actual measurement of muscle activity by surface EMG, and thus the work done by Prosser et al. was commendable [30]. In the view of cost-effectiveness, the study done by Heyrman et al. [23] used trunk variable scores (TVS) and trunk profile scores (TPS) which could be useful and prove qualitative informative. To increase the use of TPS/TVS in the interpretation of complex and interdependent head and trunk kinematic data during gait; its psychometric properties are needed to be established. In regards to the cost-effective measures, the study done by Abaid et al. [9] should also be emphasised. The study used a single axis wearable gyroscope to determine the gait characteristics of CP children with reliability. The study developed an algorithm that produced high values of sensitivity and specificity with respect to force sensitive resistors. We regard the work done by Abaid et al. [9] and suggest future studies to promote the more scientific use of such instruments.

In our review, we also found that there was also variation between the studies for data collection methodology. Most of the studies used barefoot analysis [13,15,17,18,22,23,31,32] and few used assistive device like foot arthrosis and treadmill walking [17,35]. In regards to the walkway, 10 m was used by the majority of the studies except few studies conducted by Saether et al. [21], Krautwurst et al. [28] and Bartonek et al. [15] which used a walkway of 5, 7 and 12 m, respectively. It is important to understand that inconsistent in study methodology between the studies could be a major source of changes in findings between the studies. The kinematic and kinetic findings among the review studies have been reported as below.

Kinematic variables: Various head and trunk kinematics outcome measures were reported in the review studies (Table 3). Some important findings have been discussed in brief as below:

a) Head attenuation with respect to trunk and pelvis

3D acceleration, angular velocity and magnetic field vector for head attenuation were reported in the study done by Summa et al. [16]. The study reported that there was a significant reduction in acceleration from pelvis to sternum in CP children compared to TD and they showed negative sternum to head attenuation (−15.08 ± 24.16, p = .001). This inference suggested that children with CP do not compensate for larger acceleration as seen in TD children. Therefore, it can be suggested that CP kids lack the stability of head on the trunk and cannot compensate for larger deviations in the linked head to trunk chain. The reason for reduced acceleration from pelvis to trunk could be attributed to the rigidity of the head and trunk system. On the contrary, a study done by Wallard et al. [6] reported no statistically significant difference differences in maximum and minimum head angle amplitude in the sagittal plane between CP and TD children. From the review, it could be suggested that children with CP show decreased kinematics for head over trunk as a compensatory mechanism depending upon the severity of the disorder at a multilevel analysis.

b) Trunk, head and upper limb kinematics

In a normal walking, head, trunk and upper limb following a coordinated movement pattern for progression of a typical gait. Thus understanding these movements as single segments as well dependent segments could be very useful for insight of CP gait. The study done by Heyrman et al. [12] suggested that children with CP showed significantly increased head and trunk movements compared to TD children. In our review, we also found that the study on trunk, head and upper limb kinematics by Delabastita et al. [4] was commendable. The study explored the influence of arm swing and walking speed on trunk sway in CP children compared to age-matched TD. The study concluded that the trunk sway velocity increased with increase in walking speed in CP. The change was more in hemiplegic CP compared to diplegic CP and TD. It could be easily understood that hemiplegic CP showed greater sway as one side of the muscle were more affected and thus difficult to control. Similarly, trunk sway velocity increased more with both arm restriction compared to single arm restriction. This result suggests that CP children also use arm swing for gait balance as normal TD children. Also, promoting more arm swing could be used as a treatment technique for reducing the trunk sway among CP children. Upper limb kinematics was reported by two authors [17,18]. The former study done by Galli et al. [17] reported data for CP on the upper limb, thorax, spine and pelvis kinematics with barefoot walking and walking with heel ankle foot orthosis (hAFO). The study suggested that hemiplegic CP children held elbow at higher flexion compared to TD. This could be seen as a balancing strategy to keep the centre of gravity and mass within the control. The study also found that the ROM for trunk, spine and pelvis was significantly increased compared to TD in both barefoot walking and walking with the orthosis. Increased ROM s could be seen due to muscular weakness and altered tone in CP children. Similar results were reported by the second study done by Schweizer et al. [18]. Also, the study done by Galli et al. [17] suggested significantly increased shoulder abduction in CP compared to TD. This could be seen as the compensatory strategy for balance and postural control. This means that trunk and spine work moreover like a single segment showing a complex gait for CP children. In our review, we also found that the changes in kinematics at head, trunk and upper limb also depend on the type of CP. The study done by Heyrman et al. [23] reported significant changes in head and trunk kinematics in children with SD during gait using a clinically oriented model with established reliability. The study also suggested that CP children with GMFC level 2 walked slowly with smaller step length than those of GMFCS 1 and TD children. As walking speed influences segmental kinematics and determined by the level of disorder, this may have influenced results. Thus changes in spatio-temporal parameters of the gait could have also influenced the head and trunk kinematics in CP children. Therefore, head and trunk kinematics should be interpreted with caution due to increased variability of its position during gait in CP, especially in the sagittal and transverse plane. It is also very important to consider that primary impairments reflecting deficient head and trunk control may not be distinguished from compensatory movements induced by lower limb pathology in CP gait. Since none of the studies reported these findings with rigorous scientific agreements, it could not be quantified how much head and trunk kinematics changes should be expected with change in lower limb. Therefore, our review suggests that head and trunk movements should also be assessed as dependent segments while study lowers limb biomechanics. In regards to these findings, the study conducted by

Heyrman et al. [25] developed a Trunk control measurement scale with good reliability and found that children with spastic CP showed an impaired trunk control with a median score of 38.5 out of 58 [24]. Therefore, studies relating head and trunk kinematics with lower limb kinematics, kinetics and muscle activity would contribute to the understanding of the functional relationship between segments and further report whether the observed movement deficits may be defined as primary impairments or as compensatory movements. The compensatory strategy of the trunk during CP gait has been well challenged [23]. The aim of the study done by Heyrman et al. [23] was to determine whether the altered trunk movements in CP gait was a compensatory mechanism or it occurred due to underlying trunk control deficit and lower limb pathology. This was a great research which clearly gave a scientific base to understand the altered head and trunk movements in a CP gait. In addition to gait analysis, the study found a correlation between TPS and TVS at sitting and walking. The results from the study suggested a significant correlation of poor performance of trunk control measurement scale (TCMS) in sitting with increased thorax ROM and TPS/TVS. These results could be clearly an indicative of underlying trunk control deficit. No significant correlation was found between the TPS and gait profile score (GPS), suggesting that overall trunk and lower limb movement deficits were not strongly associated. This study provided the first evidence that the altered trunk movements observed during gait should not be solely considered compensatory due to lower limb impairments. The study done by Iosa et al. [29] found that children with CP find difficulty in managing upper body accelerations while moving rapidly as compensation strategy.

c) Thorax kinematics

The movements of head and trunk are influenced by the biomechanical linkage with the close kinematic chain of the thorax. A study proposed that the thorax exhibited significantly larger ROM for CP in the frontal plane compared to TD children [12]. This suggests that the changes in head and trunk medial and lateral deviations could be seen as a consequent changes in the thorax kinematics. In support of these findings, the results from two previous studies done by Summa et al. [16] and Bonnefoy-mazure [22] concluded that CP children walked with significant higher thorax tilt and obliquity compared to TD. The mean thorax ROM for thorax tilt in diplegic CP was found to be 8.77° compared to 4.33° in TD (p=.001). Similar trend for hemiplegic was seen with thorax tilt of 7.1° compared to 4.34° in TD. Thorax obliquity was also significantly greater with 12.16° in diplegic CP compared to 3.78 in TD. The segmental analysis of trunk kinematics by Attias et al. [20] was an excellent finding. Thorax is a biomechanically linked segment with trunk and upper limb and could play an important role in gait characteristics. The study also concluded that greater thorax movement is responsible for greater levels of impairments in CP. In addition, the study conducted by Romkes et al. [34] suggested increased forward tilt of the thorax for CP children over the entire gait cycle. These factors highlight the importance of thorax kinematics in CP gait.

d) Lumbo-pelvic kinematics

The movement analysis of lumbar and pelvic segments among CP children has been scarce in previous studies. In this regards, only one study conducted by Kiernan et al. [14] provided deeper insights to CP gait characteristics. The study found that children with CP and GMFCS II and III showed a statistically significant increased flexion ROM in the lumbar segment compared to both GMFCS I and TD in the sagittal plane (6.3° and 8°, respectively) [14]. However, no significant difference was found in the frontal and transverse plane. The study also found a significant correlation between lumbar segment kinematics. From these findings, the study suggested that increased anterior pelvic tilt which indeed is a characteristic of CP gait could lead to increased lumbar lordosis and flexed lumbar segment position during CP gait. The flexion could be more with increasing level of impairments. Failure of abdominal muscles to control the segment could also be a potential factor. It could also be seen as a compensatory mechanism for better thorax-pelvic alignment. Our systematic review of the related literature suggested that the findings of this study were very useful as well as the argument suggested was scientifically sound and rational.

Trendelenburg is a common presentation in children with CP. The study conducted by Krautwurst et al. [28] investigated a correlation of hip abductors with trunk and pelvis motions. A total of 375 spastic bilateral CP children were compared with 24 TD children. The study found a strong and significant correlation between trunk lean and hip abductor strength suggesting that like TD children, hip abductor weakness is responsible for ipsilateral leaning in CP with no compensatory changes in pelvic motions. The findings of this study also indicated that pelvic position should retain more importance than trunk positions.

Kinetics: Apart from kinematic analysis, the kinetic analysis of head and trunk in children with CP could be a very important clinical finding. Understanding the joint force and muscular forces could be beneficial for therapeutic and rehabilitation purpose. Poor postural control due to reduced muscular strength is a common characteristic of CP gait. In our system review, we found that the literature regarding the head and trunk kinetics in CP is limited. Since muscular activity and recruitment pattern determine the strength and force, it would be highly important to investigate the kinetics of hip and trunk through EMG analysis. The study performed by Prosser et al. [30] established foundation for joint kinetics analysis by studying the muscular activity of hip and trunk muscles in CP population. The study collected EMG data from 15 CP to 16 TD children and compared activation frequency. The study found that the instantaneous mean frequency (IMF) was significantly higher for CP group. This demonstrated altered patterns of trunk and hip muscle activation as suggested by increased rates of motor unit firing and their recruitment. Clearly, this could be responsible for altered joint and muscle forces leading to early fatigue and biomechanical efficiency in CP children. Adding more to altered kinetics, the study done by Krautwurst et al. [28] found that weakness in hip abductor was also accompanied by decreased hip abduction moment. Due to lateral leaning, the normal loading response could be altered. Also, the study done by Kiernan et al. [14] found a correlation between lumbar L5 and sacral S1 reactive force and moment. As the lumbar ROM increased, the loading increased on the lumbo-pelvic segment. Thus findings from the review suggest that kinetic analysis of the CP gait have high clinical importance and should be investigated in more detail.

Future suggestions

The studies in this review have children classified according to gross motor function classification, but do not consider the cognitive impairments of CP children which are important as they might affect the walking performance. Almost all the studies compared a pathologic gait pattern with a healthy one and interpreted accordingly. However, this method does not allow a clear distinction between primary and secondary deviations or further compensatory mechanisms. Therefore, a follow up as a case study would be more useful to determine the musculoskeletal changes and compensatory strategies over time. Given that the head is an independently moving segment with few mechanical constraints; numerous positions in space are possible, which vastly hinders standardisation. Minor visual or auditory stimuli may induce changes in head position attributing to an increased variability which would hamper results. Based on our review, it could be suggested that variability exists between the studies for reporting head and trunk kinematics. However, a fixed mechanism to explain these changes may not be possible due to variant manifestation of the disorder itself. Therefore, categorisation of CP based on GMFCS could be an important step to fill this gap.

Conclusion

In this review study, we conclude that children with CP have a significant difference in head and trunk kinetics and kinematics compared to age-matched TD children. It appears that it is difficult for children with CP to dissociate rotations of the head from those of the trunk. Treatment planning should include a careful evaluation of the pathologic gait pattern using computerised 3-dimensional gait analyses including surface EMG and force platforms with special attention to possible compensatory mechanisms.

Declaration of interest

The authors report no declarations of interest.

References

1. Kharb A, Saini V, Jain YK, et al. A review of gait cycle and its parameters. *J Glob Optim* 2011;**13**:78–83.

2. Mazzà C, Zok M, Cappozzo A. Head stabilization in children of both genders during level walking. *Gait Posture*. 2010;**31**:429–432. 30

3. Sankar C, Mundkur N. Cerebral palsy-definition, classification, etiology and early diagnosis. *Indian J Pediatr*. 2005;**172**:865–868.

4. Delabastita T, Desloovere K, Meyns P. Restricted arm swing affects gait stability and increased walking speed alters trunk movements in children with cerebral palsy. *Front Hum Neurosci*. 2016;**10**:354.

5. Torricelli D, Gonzalez J, Weckx M, et al. Human-like compliant locomotion: state of the art of robotic implementations. *Bioinspir Biomim*. 2016;**11**:051002.

6. Wallard L, Bril B, Dietrich G, et al. The role of head stabilization in locomotion in children with cerebral palsy. *Ann Phys Rehabil Med*. 2012;**55**:590–600.

7. Wallard L, Dietrich G, Kerlirzin Y, et al. Balance control in gait children with cerebral palsy. *Gait Posture*. 2014;**40**:43–47.

8. Senden R, Grimm B, Heyligers IC, et al. Acceleration-based gait test for healthy subjects: reliability and reference data. *Gait Posture*. 2009;**30**:192–196.

9. Abaid N, Cappa P, Palermo E, et al. Gait detection in children with and without hemiplegia using single-axis wearable gyroscopes. *PLoS One*. 2013;**8**:e73152.

10. Tugui RD, Antonescu D. Cerebral palsy gait, clinical importance. *Maedica*. 2013;**8**:388.

11. Heyrman L, Feys H, Molenaers G, et al. Reliability of head and trunk kinematics during gait in children with spastic diplegia. *Gait Posture*. 2013;**37**:424–429.

12. Heyrman L, Feys H, Molenaers G, et al. Three-dimensional head and trunk movement characteristics during gait in children with spastic diplegia. *Gait Posture*. 2013;**38**:770–776.

13. Bartonek A, Lidbeck CM, Gutierrez-Farewik EM. Influence of external visual focus on gait in children with bi-lateral cerebral palsy. *Pediatr Phys Ther*. 2016;**28**:393.

14. Kiernan D, Malone A, Brien TO, et al. Gait & posture three-dimensional lumbar segment movement characteris-tics during paediatric cerebral palsy gait. *Gait Posture*. 2017;**53**:41–47.

15. Bartonek A, Lidbeck C, Hellgren K, et al. Head and trunk movements during turning gait in children with cere-bral palsy. *J Mot Behav*. 2018:1–9.

16. Summa A, Vannozzi G, Bergamini E, et al. Multilevel upper body movement control during gait in children with cerebral palsy. *PloS One*. 2016;**11**:e0151792.

17. Galli M, Cimolin V, Albertini G, et al. Original article kinematic analysis of upper limb during walking in diple-gic children with cerebral palsy. *Eur J Paediatr Neurol*. 2014;**18**:134–139.

18. Schweizer K, Brunner R, Romkes J. Clinical biomechanics upper body movements in children with hemiplegic cerebral palsy walking with and without an ankle-foot orthosis. *JCLB*. 2014;**29**:387–394.

19. Malone A, Kiernan D, French H, et al. Do children with cerebral palsy change their gait when walking over uneven ground? *Gait Posture*. 2015;**41**:716–721.

20. Attias M, Bonnefoy-mazure A, Lempereur M, et al. Clinical biomechanics trunk movements during gait in cere-bral palsy. *Clin Biomech*. 2015;**30**:28–32.

21. Saether R, Helbostad JL, Adde L, et al. Research in developmental disabilities gait characteristics in children and adolescents with cerebral palsy assessed with a trunk-worn accelerometer. *Res Dev Disabil*. 2014;**35**:1773–1781.

22. Bonnefoy-Mazure A, Sagawa Y, Lascombes P, et al. Research in developmental disabilities A descriptive analy-sis of the upper limb patterns during gait in individuals with cerebral palsy. *Res Dev Disabil*. 2014;**35**:2756–2765.

23. Heyrman L, Desloovere K, Molenaers G, et al. Research in developmental disabilities. altered trunk movements during gait in children with spastic diplegia: compensatory or underlying trunk control deficit? *Res Dev Disabil*. 2014;**35**:2044–2052.

24. 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**:327–334.

25. Heyrman L, Molenaers G, Desloovere K, et al. A clinical tool to measure trunk control in children with cerebral palsy: the trunk control measurement scale. *Res Dev Disabil*. 2011;**32**:2624–2635.

26. Bonnefoy-Mazure A, Turcot K, Kaelin A, et al. Full body gait analysis may improve diagnostic discrimination between hereditary spastic paraplegia and spastic diplegia: a preliminary study. *Res Dev Disabil*. 2013;**34**:495–504.

27. Bonnefoy-Mazure A, Sagawa Y, Lascombes P, et al. Research in developmental disabilities identification of gait patterns in individuals with cerebral palsy using multiple correspondence analysis. *Res Dev Disabil*. 2013;**34**:2684– 2693.

28. Krautwurst BK, Wolf SI, Heitzmann DWW, et al. Research in developmental disabilities the influence of hip abductor weakness on frontal plane motion of the trunk and pelvis in patients with cerebral palsy. *Res Dev Disabil*. 2013;**34**:1198–1203.

29. Iosa M, Marro T, Paolucci S, et al. Research in developmental disabilities stability and harmony of gait in chil- dren with cerebral palsy. *Res Dev Disabil*. 2012;**33**:129–135.

30. Prosser LA, Lee SCK, Barbe MF, et al. Trunk and hip muscle activity in early walkers with and without cerebral palsy – A frequency analysis. *J Electromyogr Kinesiol*. 2010;**20**:851–859.

31. Hsue B, Miller F, Su F. The dynamic balance of the children with cerebral palsy and typical developing during gait. Part I: spatial relationship between COM and COP trajectories. *Gait Posture*. 2009;**29**:465–470.

32. Hsue B, Miller F, Su F. The dynamic balance of the children with cerebral palsy and typical developing during gait part II: instantaneous velocity and acceleration of COM and COP and their relationship. *Gait Posture*. 2009;**29**:471–476.

33. Redekop S, Andrysek J, Wright V. Single-session reliability of discrete gait parameters in ambulatory children with cerebral palsy based on GMFCS level. *Gait Posture*. 2008;**28**:627–633.

34. Romkes J, Peeters W, Oosterom AM, et al. Evaluating upper body movements during gait in healthy children and children with diplegic cerebral palsy. *J Pediatr Orthop B*. 2007;**16**:175–180.

35. Holt KG, Ratcliffe R, Jeng SF. Head stability in walking in children with cerebral palsy and in children and adults without neurological impairment. *Phys Ther*. 1999;**79**:1153–1162.