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Short communication

The impact of centre of pressure error on predicted joint kinetics during cerebral palsy and typically developed gait: A clinical perspective ☆

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ABSTRACT

Centre of Pressure (CoP) location error is common when using kinematic and kinetic data to predict intersegmental forces and net joint moments during gait. Changes in peak moments due to CoP error have been reported in the literature. However, debate exists as to what levels of error are acceptable. The aim of this study was to examine the impact of CoP error on the kinetic profiles of children with typical development (TD) and children with cerebral palsy (CP) during gait. Three-dimensional kinematic and kinetic data were recorded and simulated CoP errors were applied at 3 mm, 6 mm, 9 mm, 12 mm increments in both positive and negative anteroposterior and mediolateral directions. Absolute differences in maximum kinetic parameters between increments were assessed in conjunction with changes in the Gait Deviation Index-Kinetic (GDI-Kinetic). Changes in GDI-Kinetic above 3.6 points were considered clinically significant. Maximum peak changes of up to 24.8% (CP) and 34.7% (TD) (sagittal plane) and up to 36.8% (CP) and 61.5% (TD) (coronal plane) were demonstrated at the knee. While absolute percentage differences were high at some error increments, GDI-Kinetic results suggested that such large percentage differences may still be clinically acceptable. Children with TD demonstrated clinically significant changes in GDI-Kinetic for CoP displacements of 9 mm and 12 mm, corresponding to 23% and 35% absolute differences in maximum moments. In contrast, the clinically significant threshold was not reached for children with CP that may be related to a slower walking speed. The findings of this study highlight the need for laboratories to consider the thresholds currently used for CoP error, which will help guide quality assurance procedures.

1. Introduction

Inverse dynamic analysis is a procedure routinely used in gait laboratories where measured kinematic and ground reaction force (GRF) data are combined with anthropometric data to predict intersegmental forces and net joint moments during gait (Davis et al., 1991, Kingma et al., 1996). There are a number of potential sources of error in these calculations. Centre of pressure (CoP) location error is one such example. Inaccuracies may occur when GRF measured by a force plate is not correctly spatially transformed into the laboratory coordinate system (Holden et al., 2003). Investigation into the impact of CoP location error on kinetics during gait has been examined (Camargo-Junior et al., 2013, McCaw and DeVita, 1995, Nissan, 1980) but debate still remains as to acceptable levels of error. A standard gait laboratory procedure to measure this error is the pole test, whereby, a metal pole with markers attached is applied to a force plate and the anteroposterior and mediolateral distance between the application of the tip of the pole on the plate and the resultant CoP location is calculated (Baker, 1997, Holden et al., 2003, Lewis et al., 2007). Various levels of error have been reported for this test for varying types of force plates. Location errors of up to 30 mm have been reported for piezoelectric force platforms before correction algorithms have been applied and 5.8 mm (±3.7 mm) after correction (Schmiedmayer and Kastner, 1999, Schmiedmayer and Kastner, 2000). Lewis and colleagues report slightly larger errors after correction of up to 10.8 mm and use a value of 12 mm as a pass/fail threshold for their quality assurance check (Lewis et al., 2007). Indeed this threshold is used in many laboratories, including our own. However, the authors state that this threshold is a matter of judgement. Some studies have suggested that errors of 10 mm are a matter for concern, with inaccuracy in the resultant moments as much as 14% of maximum value (McCaw and DeVita, 1995).

☆ "Each of the authors has read and concurs with the content in the final manuscript. The material within has not been and will not be submitted for publication elsewhere except as an abstract."

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Other studies report inaccuracy at 10 mm to be as much as 28% of maximum moments depending on velocity, with the knee joint moment most affected (Camargo-Junior et al., 2013). Consequently, a limit of 12 mm of error may then be too large to be considered acceptable. As the majority of clinical gait laboratories assess children with cerebral palsy (CP), who generally walk slower than children with typical development (TD), it is therefore important to consider the effect of CoP location error on this population. It is possible that the impact of CoP location error may not be as significant in these children at slower walking speeds and consequently higher thresholds of CoP location error may be acceptable. However, before we can decide what is or is not acceptable, errors in kinetic calculations need to be considered from a clinical perspective. That is, would a location error of 10 mm, affecting maximum moment by as much as 14%, be likely to influence the clinical decision making process? With such questions in mind, the objective of this study was to examine the impact of CoP location error on the kinetic profiles of children with both TD and CP from a clinical perspective using the GDI-Kinetic as clinical outcome measure (Rozumalski and Schwartz, 2011), with the aim of determining a suitable level of error that could be used to guide the gait laboratory quality assurance procedure. The GDI-Kinetic is a multivariate measure of overall gait pathology based on joint kinetics where a change in GDI-Kinetic score of 3.6 points has been shown to be clinically significant (Kiernan et al., 2014).

2. Materials and methods

2.1. Subjects

Twelve children who presented for routine gait analysis with a diagnosis of diplegic CP and 12 children with TD were retrospectively included in this study (Table 1). Informed written consent was obtained from all participants and from their parents when legally minor. The study was approved by the host institution's Ethical Committee.

Table 1
Subject Demographic data for children with CP and TD (Note: *walking speed was significantly slower for children with cerebral palsy at $p < 0.05$).

Parameter	CP Mean (SD) n = 12	TD Mean (SD) n = 12
Male/Female	10/2	9/3
Age	10.2(2.1)	8.5(1.2)
Height	1.42(0.13)	1.34(0.1)
Weight	35.8(11.9)	29.1(6.0)
Walking Speed*	1.14 (0.10)	1.33(0.14)

2.2. Data collection

A full barefoot 3-dimensional kinematic and kinetic analysis was performed using the CODA cx1 active marker system (Charnwood Dynamics Ltd., Leicestershire). Kinematic data were captured at 200 Hz with the marker placement protocol and underlying mathematical model implemented as previously described (Kiernan et al., 2016). Two Kistler 9281B force platforms were used to measure GRF data at 400 Hz. All kinematic and kinetic calculations were performed in Codamotion ODIN 2.01 Build 10 00. GDI-Kinetic calculations were performed using custom scripts in MATLAB 8.1.0.604 (The MathWorks, Natick, Massachusetts, USA). As CoP location error only affects data throughout the stance phase of gait, only stance phase data were reported. A full description of marker set and segment coordinate system definitions have been included as supplementary material (Appendix 1).

2.3. CoP location error

CoP location error was applied on each representative file using custom Python scripts run through the Codamotion ODIN software. Per standard lab protocol, correction algorithms for piezoelectric platforms were applied prior to kinetic data calculation (Schmiedmayer and Kastner, 1999). A recent pole test averaged at 5 points on each platform across the two 9281B force platforms measured the error of the system at 3.5 mm (X-direction) and 3.4 mm (Y-direction) after the piezoelectric correction algorithms were applied. For the purposes of this study, error increments of 3 mm were then applied to the CoP measured by the system for each subject in anterior, posterior, medial and lateral directions up to a maximum of 12 mm as defined by the reference frame of the force plate for which the foot was in contact. Children walked in both directions along the lab walkway with direction of travel accounted for in the CoP location error calculations. Additional ensemble average profiles have been included as supplementary data (Appendices 2–11).

2.4. Data Analysis:

The GDI-Kinetic was used as a tool to determine whether any clinically meaningful important difference (CMID) existed in the kinetic profiles between error increments (Rozumalski and Schwartz, 2011). The GDI-Kinetic is a multivariate measure of

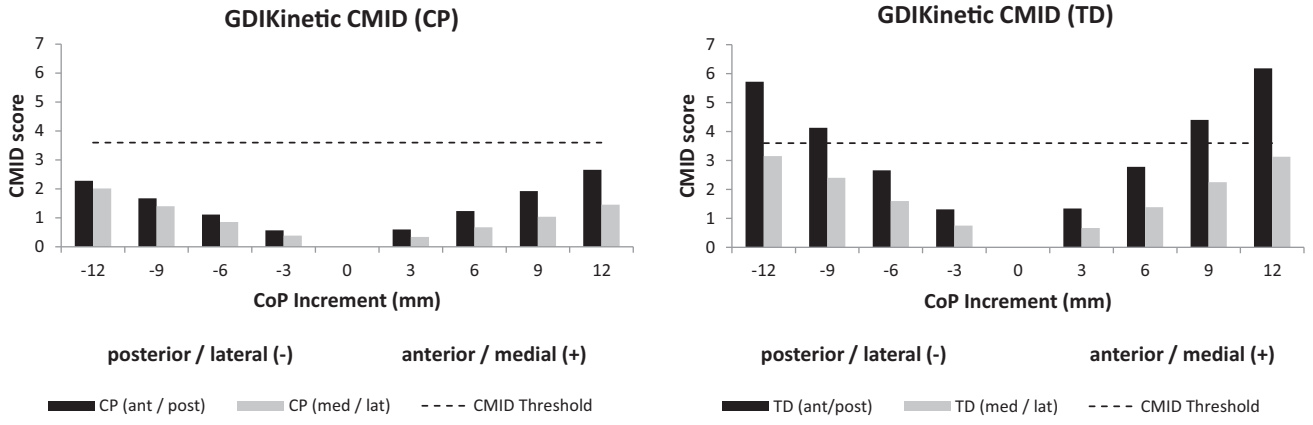

Fig. 1. Mean plus 1 standard deviation GDI-Kinetic CMID scores for TD and CP children. Note that differences above the CMID were present for children with typical development at ±9 mm and ±12 mm in the anteroposterior direction.

Table 2
Mean maximum values and absolute percentage change for joint moments and powers in children with CP at staged increments in anteroposterior (positive and negative X) and mediolateral (positive and negative Y) directions.

Offset (mm)	Centre of Pressure Offset - Anteroposterior direction						Offset (mm)	Centre of Pressure Offset – Mediolateral Direction					
	Max Moments sagittal plane (Nm/kg)	Mean Absolute percentage change (%)	Max Moments coronal plane (Nm/kg)	Mean Absolute percentage change (%)	Max Power (W/kg)	Mean Absolute percentage change (%)		Max Moments sagittal plane (Nm/kg)	Mean Absolute percentage change (%)	Max Moments coronal plane (Nm/kg)	Mean Absolute percentage change (%)	Max Power (W/kg)	Mean Absolute percentage change (%)
Hip							**Hip**						
12	1.263	11.13(4.2)	0.560	3.10 (2.3)	2.010	12.45 (7.2)	12	1.136	1.37 (1.1)	0.567	23.72 (9.8)	1.839	4.60 (3.4)
9	1.232	8.26 (3.2)	0.561	2.31 (1.8)	1.955	9.25 (5.1)	9	1.137	1.05 (0.9)	0.566	17.67 (7.4)	1.832	3.39 (2.5)
6	1.200	5.38 (2.2)	0.563	1.52 (1.3)	1.904	6.13 (3.3)	6	1.138	0.71 (0.6)	0.566	11.70 (4.8)	1.825	2.18 (1.6)
3	1.170	2.60 (1.1)	0.565	0.76 (0.7)	1.857	2.99 (1.6)	3	1.139	0.44 (0.4)	0.567	5.80 (2.3)	1.818	0.96 (0.8)
SP	**1.142**	**–**	**0.567**	**–**	**1.817**	**–**	**SP**	**1.142**	**–**	**0.567**	**–**	**1.817**	**–**
−3	1.112	2.77 (1.5)	0.570	0.76 (0.56)	1.775	3.06 (1.79)	−3	1.142	0.59 (1.06)	0.567	6.16(1.96)	1.817	1.45 (1.57)
−6	1.085	5.23 (2.35)	0.572	1.66 (1.42)	1.733	6.00 (3.11)	−6	1.145	0.93 (1.41)	0.566	12.13 (3.73)	1.814	2.62 (2.44)
−9	1.059	7.64(3.25)	0.575	2.57 (2.35)	1.692	8.94 (4.47)	−9	1.148	1.32 (1.84)	0.567	18.15 (5.58)	1.808	3.78 (3.36)
−12	1.034	9.89 (3.98)	0.577	3.49 (3.26)	1.652	11.74 (5.78)	−12	1.151	1.75 (2.30)	0.567	24.08 (7.38)	1.806	4.92 (4.19)
Knee							**Knee**						
12	0.537	19.26 (14.3)	0.298	9.74 (6.6)	0.983	29.69(18.8)	12	0.667	3.15 (18.5)	0.278	29.10 (17.4)	1.023	6.26 (5.7)
9	0.565	14.67 (11.9)	0.295	7.16 (4.9)	0.983	22.13 (13.3)	9	0.663	2.37 (13.9)	0.278	21.77 (13.3)	1.017	4.56 (4.2)
6	0.593	9.81 (9.0)	0.292	4.79 (3.5)	0.986	14.79 (8.0)	6	0.659	1.55 (9.2)	0.279	14.78 (8.8)	1.012	3.10 (2.9)
3	0.622	4.82 (4.7)	0.289	2.42 (1.8)	0.995	7.385 (4.3)	3	0.656	0.71 (4.6)	0.282	7.693 (4.5)	1.009	1.71 (1.4)
SP	**0.652**	**–**	**0.287**	**–**	**1.003**	**–**	**SP**	**0.652**	**–**	**0.287**	**–**	**1.003**	**–**
−3	0.685	6.13 (4.44)	0.289	4.29 (10.93)	1.027	7.88 (3.90)	−3	0.651	1.72 (1.70)	0.294	10.71 (10.34)	1.004	1.80 (1.67)
−6	0.718	12.26 (8.85)	0.288	6.09 (10.81)	1.058	14.47 (7.68)	−6	0.650	3.44 (3.38)	0.299	19.51 (11.57)	1.001	3.15 (3.14)
−9	0.752	18.52 (13.24)	0.287	7.87 (10.88)	1.096	20.42 (11.57)	−9	0.648	5.15 (5.08)	0.304	28.32 (14.51)	0.998	4.73 (4.60)
−12	0.785	24.81 (17.64)	0.287	9.61 (11.01)	1.141	25.99 (13.60)	−12	0.646	6.87 (6.78)	0.310	36.80 (18.10)	0.995	6.31 (6.12)
Ankle							**Ankle**						
12	1.185	12.42 (4.7)	0.308	17.29 (17.9)	1.639	16.59 (14.1)	12	1.053	3.31 (2.0)	0.289	49.13 (20.9)	1.473	6.38 (5.1)
9	1.153	9.22 (3.4)	0.302	12.97 (13.3)	1.592	12.76 (12.1)	9	1.055	2.50 (1.5)	0.287	37.41 (16.4)	1.469	4.87 (4.2)
6	1.122	6.10 (2.2)	0.296	8.60 (8.8)	1.546	8.54 (8.0)	6	1.057	1.67 (1.0)	0.283	24.91 (13.6)	1.466	3.40 (3.3)
3	1.092	3.04 (1.01)	0.289	4.58 (4.4)	1.501	4.37 (4.0)	3	1.058	0.84 (0.6)	0.282	13.38 (10.6)	1.463	1.94 (2.7)
SP	**1.061**	**–**	**0.282**	**–**	**1.453**	**–**	**SP**	**1.061**	**–**	**0.282**	**–**	**1.453**	**–**
−3	1.029	3.09 (0.88)	0.277	4.14 (4.45)	1.410	5.28 (5.36)	−3	1.063	0.82 (0.50)	0.282	13.79 (10.73)	1.448	2.39 (2.85)
−6	0.998	6.18 (1.74)	0.271	8.30 (8.85)	1.370	9.55 (8.77)	−6	1.065	1.68 (1.00)	0.284	27.84 (21.97)	1.446	3.60 (2.83)
−9	0.966	9.25 (2.59)	0.266	12.07 (11.90)	1.332	13.65 (12.43)	−9	1.068	2.54 (1.51)	0.287	42.02 (33.43)	1.444	4.85 (3.44)
−12	0.935	12.31 (3.42)	0.260	15.53 (14.07)	1.294	17.85 (16.73)	−12	1.070	3.40 (2.02)	0.290	56.16 (45.01)	1.446	6.30 (4.47)

Table 3
Mean maximum values and absolute percentage change for joint moments and powers in children with TD at staged increments in anteroposterior (positive and negative X) and mediolateral (positive and negative Y) directions.

Offset (mm)	Centre of Pressure Offset – Anteroposterior Direction						Offset (mm)	Centre of Pressure Offset – Mediolateral Direction					
	Max Moments sagittal plane (Nm/kg)	Absolute percentage change (%)	Max Moments coronal plane (Nm/kg)	Mean Absolute percentage change (%)	Max Power (W/kg)	Mean Absolute percentage change (%)		Max Moments sagittal plane (Nm/kg)	Absolute percentage change (%)	Max Moments coronal plane (Nm/kg)	Mean Absolute percentage change (%)	Max Power (W/kg)	Mean Absolute percentage change (%)
Hip							**Hip**						
12	1.084	9.62 (4.1)	0.541	3.16 (2.2)	1.799	17.83 (6.3)	12	0.984	1.70 (1.9)	0.559	24.87 (6.3)	1.526	4.68 (3.5)
9	1.057	7.28 (3.3)	0.544	2.41 (1.8)	1.721	13.57 (5.6)	9	0.983	1.28 (1.45)	0.557	18.34 (3.4)	1.520	3.59 (2.7)
6	1.033	4.95 (2.2)	0.548	1.62 (1.24)	1.642	9.08 (4.6)	6	0.983	0.85 (0.97)	0.556	12.09 (2.4)	1.516	2.40 (1.8)
3	1.008	2.49 (1.2)	0.552	0.81 (0.6)	1.571	4.83 (2.4)	3	0.983	0.43 (0.5)	0.555	6.06 (1.2)	1.513	1.21 (0.94)
SP	**0.984**	**–**	**0.556**	**–**	**1.509**	**–**	**SP**	**0.984**	**–**	**0.556**	**–**	**1.509**	**–**
−3	0.960	2.44 (1.1)	0.560	0.81 (0.6)	1.448	4.71 (2.6)	−3	0.984	0.43 (0.5)	0.556	6.076 (1.2)	1.506	1.19 (0.9)
−6	0.937	5.03 (2.4)	0.564	1.62 (1.2)	1.395	9.57 (5.9)	−6	0.985	0.89 (1.0)	0.556	12.21 (2.7)	1.503	2.39 (1.9)
−9	0.914	7.72 (3.7)	0.568	2.43 (1.7)	1.350	14.5 (9.6)	−9	0.985	1.37 (1.5)	0.556	18.55 (4.7)	1.502	3.41 (2.4)
−12	0.893	10.3 (5.0)	0.572	3.23 (2.2)	1.311	19.7 (14.3)	−12	0.986	1.37 (1.6)	0.556	25.22 (7.78)	1.503	4.27 (2.9)
Knee							**Knee**						
12	0.521	34.69 (29.2)	0.308	10.29 (6.0)	1.209	16.32 (9.6)	12	0.667	3.69 (5.0)	0.276	61.49 (55.6)	1.070	2.70 (3.3)
9	0.555	23.45 (16.2)	0.301	7.95 (4.7)	1.154	11.80 (7.1)	9	0.667	2.80 (3.9)	0.276	39.70 (23.1)	1.066	2.09 (2.5)
6	0.590	14.45 (8.8)	0.294	5.42 (3.2)	1.106	7.89 (4.2)	6	0.664	1.90 (2.8)	0.277	24.63 (9.9)	1.062	1.44 (1.7)
3	0.625	6.77 (4.0)	0.287	2.78 (1.7)	1.073	4.11 (2.4)	3	0.663	0.97 (1.5)	0.279	11.92 (3.9)	1.059	0.74 (0.9)
SP	**0.662**	**–**	**0.281**	**–**	**1.056**	**–**	**SP**	**0.662**	**–**	**0.281**	**–**	**1.056**	**–**
−3	0.698	6.77 (3.9)	0.274	2.78 (1.7)	1.049	4.54 (2.2)	−3	0.660	0.97 (1.5)	0.282	11.88 (3.9)	1.054	0.73 (0.9)
−6	0.734	12.45 (6.5)	0.267	5.76 (3.6)	1.050	8.71 (4.9)	−6	0.659	1.97 (3.2)	0.284	24.04 (8.1)	1.054	1.31 (1.5)
−9	0.771	17.34 (8.3)	0.261	8.98 (5.8)	1.061	12.4 (5.5)	−9	0.658	3.03 (5.1)	0.287	37.77 (15.9)	1.054	1.85 (2.2)
−12	0.807	21.63 (9.5)	0.254	12.48 (8.3)	1.071	16.31 (7.2)	−12	0.657	3.91 (6.16)	0.291	53.63 (28.4)	1.054	2.4 (3.0)
Ankle							**Ankle**						
12	1.335	9.97 (0.8)	0.332	11.16 (3.6)	3.403	13.12 (16.1)	12	1.202	3.21 (1.25)	0.297	64.68 (50.2)	3.073	7.03 (3.1)
9	1.303	7.26 (0.6)	0.323	8.60 (2.8)	3.324	9.51 (9.6)	9	1.202	2.40 (0.93)	0.297	41.52 (24.0)	3.076	5.24 (2.9)
6	1.270	5.25 (0.4)	0.314	5.91 (1.9)	3.245	6.24 (5.3)	6	1.203	1.59 (0.61)	0.296	25.08 (10.7)	3.079	3.47 (1.51)
3	1.238	2.69 (0.22)	0.305	3.06 (1.1)	3.167	3.09(2.2)	3	1.204	0.80 (0.3)	0.296	11.85 (3.8)	3.083	1.72 (0.76)
SP	**1.206**	**–**	**0.296**	**–**	**3.088**	**–**	**SP**	**1.206**	**–**	**0.296**	**–**	**3.088**	**–**
−3	1.174	2.70 (0.2)	0.287	3.06 (1.1)	3.009	3.12 (2.3)	−3	1.207	0.80 (0.3)	0.296	11.85 (3.8)	3.093	1.73 (0.8)
−6	1.141	5.54 (0.5)	0.278	6.32 (2.3)	2.931	6.29 (4.1)	−6	1.208	1.59 (0.6)	0.296	23.17 (6.8)	3.099	3.48 (1.6)
−9	1.109	8.55 (0.8)	0.269	9.80 (3.6)	2.853	9.54 (5.6)	−9	1.209	2.38 (0.9)	0.297	35.20 (12.6)	3.105	5.22 (2.4)
−12	1.077	11.73 (1.1)	0.260	13.51 (5.1)	2.775	12.85 (6.5)	−12	1.210	3.17 (1.2)	0.298	49.44 (25.8)	3.112	6.94 (3.2)

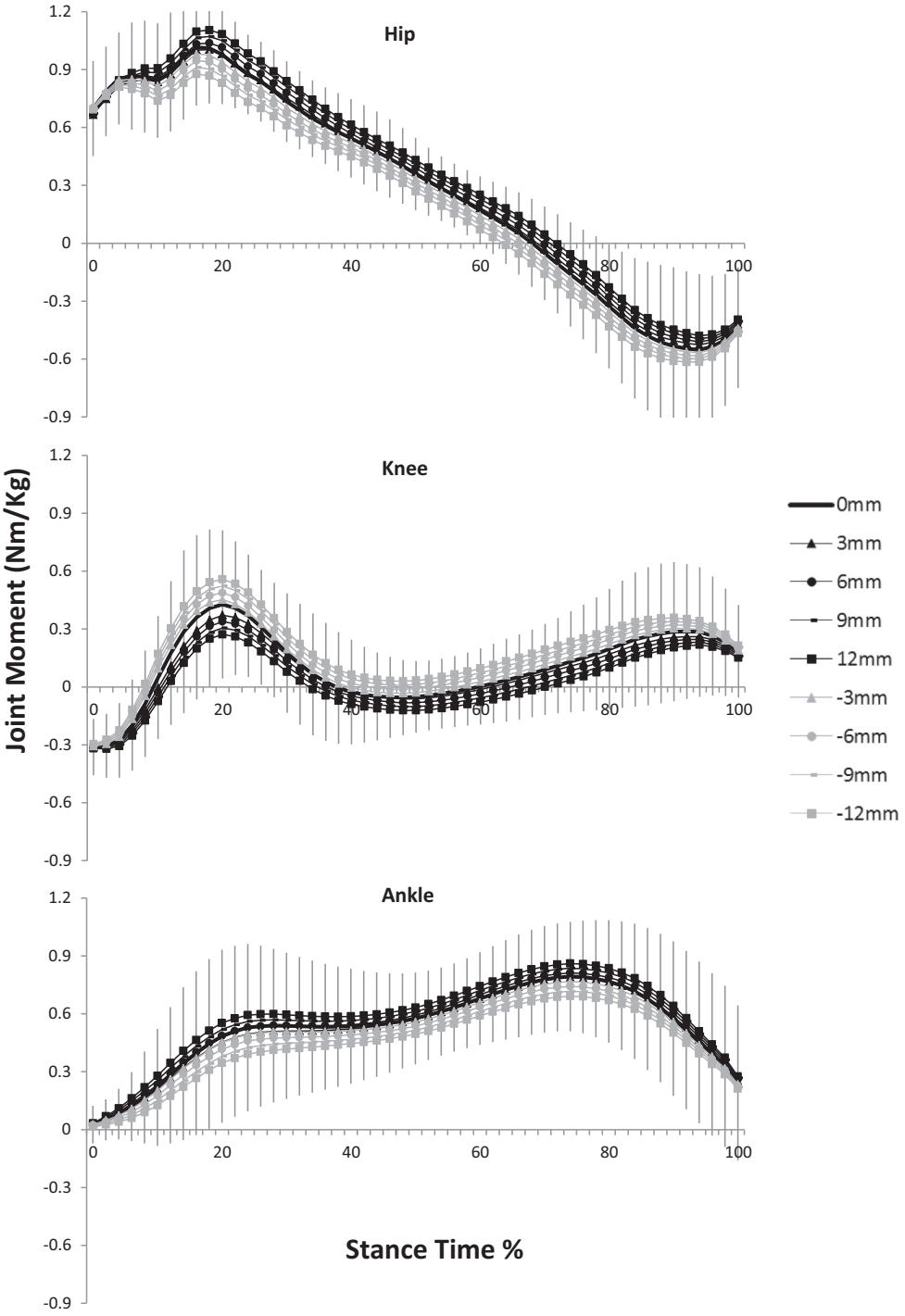

Fig. 2. Ensemble average moment profiles at the ankle, hip and knee in the sagittal plane for children with CP. The solid black line represents the mean CoP starting point (0 mm) with the vertical error bars representing ±1 standard deviation (SD) from mean. Error was applied in the anteroposterior direction. Note: No error increment resulted in an offset in moment profile outside the ±1 SD band for children with CP.

overall gait pathology based on joint kinetics. The GDI-Kinetic intuitively scales the distance between the kinetics of a pathological gait pattern to those of the average normal gait pattern. A GDI-Kinetic score $\geq$ 100 indicates a subject whose kinetics are no further away from the mean control than would be expected of a subject with normal gait (Rozumalski and Schwartz, 2011). The GDI-Kinetic score was calculated for each leg and the mean difference plus 1 standard deviation between error increments was used as a measure CMID. A threshold CMID of 3.6 points was used for this study based on a method as previously reported (Kiernan et al., 2014, Kiernan et al., 2015). A linear regression was applied to the GDI –Kinetic data to determine the CoP location error at which this clinical significance threshold was crossed.

Absolute differences in maximum kinetic parameters between the starting CoP location and the corresponding incremented error points in anterior, posterior, medial and lateral directions were calculated for each subject for each leg. The mean absolute difference (expressed as a % of starting CoP value) for the following variables were reported: sagittal and coronal hip, knee and ankle moments and hip, knee and ankle power. Sign conventions were as follows:

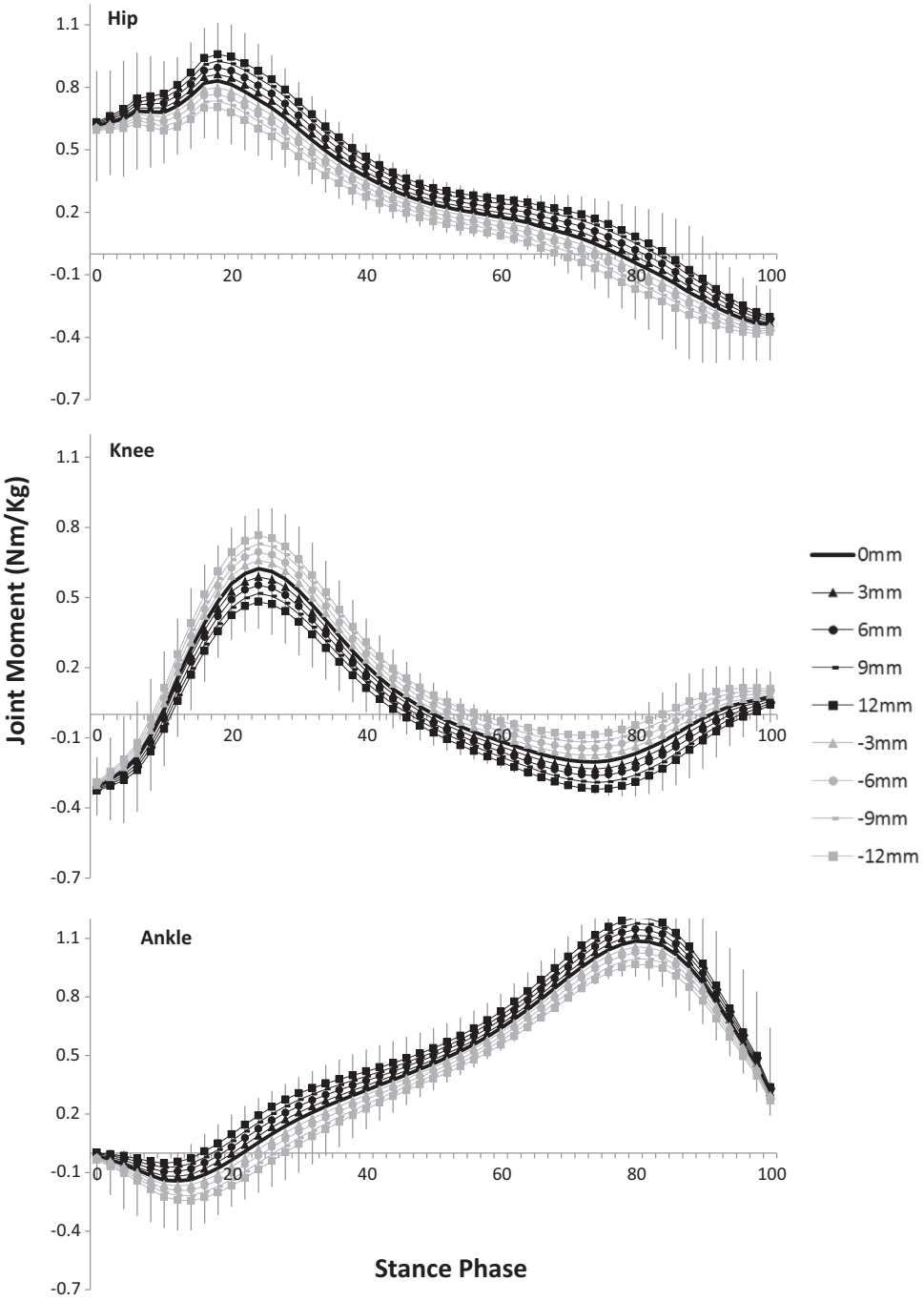

Fig. 3. Ensemble average moment profiles at the ankle, hip and knee in the sagittal plane for children with TD. The solid black line represents the mean CoP starting point (0 mm) with the vertical error bars representing ±1 standard deviation (SD) from mean. Error was applied in the anteroposterior direction. Note: No error increment resulted in an offset in moment profile outside the ±1 SD band for children with TD.

Hip moments: extensor & abductor positive; Knee moments: extensor and valgus positive; Ankle moments: plantarflexor and pronator positive; Hip, knee and ankle power: generation positive.

3. Results

3.1. GDI – kinetic

Only children with TD demonstrated differences above the CMID threshold (Fig. 1). In both the anterior (positive X) and posterior (negative X) directions, children with TD were above the CMID threshold at 9 mm and 12 mm (Fig. 1). Neither group demonstrated a CMID above the threshold medially (positive Y) or laterally (negative Y) (Fig. 1). A linear regression determined 7.3 mm (anterior) and 7.8 mm (posterior) as the points at which GDI-Kinetic matched the CMID threshold for children with TD.

3.2. Maximum joint moments and powers

Percentage changes in maximum moments and powers increased at all levels of the hip, knee and ankle for both groups as the CoP increment was positioned further away from the CoP starting location (Tables 2 and 3). Maximum knee moment in the sagittal plane, with increments offset in the anteroposterior direc-

tion, demonstrated the largest absolute percentage change in moment calculations for both groups (TD: 35% (+12 mm) and 22% (-12 mm); CP: 19% (+12 mm) and 25% (-12 mm)). Maximum ankle power in the coronal plane, with increments offset in the mediolateral direction, demonstrated the largest absolute percentage change in power calculations (TD: 65% (+12 mm) and 49% (-12 mm); CP: 49% (+12 mm) and 56% (-12 mm)) (Tables 2 and 3).

4. Discussion

The purpose of this study was to examine the impact of CoP location error on kinetic calculations during both TD and CP gait. Using the GDI-Kinetic as a clinical outcome measure, results suggested error of 9 mm and above, specifically in the anteroposterior direction, could be interpreted as clinically meaningful for the TD group (Fig. 1). When investigated further, the lowest clinically significant increment for TD was at 7.3 mm (anterior) suggesting that if CoP location error was known to be present above this value then the resultant kinetics should to be considered with caution. Interestingly, the CMID threshold was not reached for children with CP. It has been suggested that the overall impact of CoP location error increases with velocity, with the knee joint most affected (Camargo-Junior et al., 2013). As children with TD in this study walked faster (1.33 m/s (TD); 1.14 m/s (CP), $p < 0.05$), and demonstrated increased range of joint moments at the knee compared to children CP (Figs. 2 & 3), joint moments of children with TD may be more sensitive to CoP location error in the anteroposterior direction as a result. Interestingly, when these changes in GDI-Kinetic were considered in conjunction with ensemble average profiles, all kinetic profiles remained within the starting CoP mean (±SD) band although the GDI-Kinetic results demonstrated CMIDs at increments as low as 7.3 mm for children with TD. This suggested that a visual interpretation of CoP location error alone may not be enough to identify concerning levels of error.

An examination of the absolute percentage change in maximum values demonstrated that, with increments offset in the anteroposterior direction, the knee joint had the greatest change in maximum moment for both groups (CP range: 5–25%; TD range: 7–35%). These values were in line with those of other studies (McCaw and DeVita, 1995). However, when considered with the GDI-Kinetic, results suggested that a substantial absolute percentage change was acceptable at the knee before being considered clinically significant (e.g. Anteroposterior direction: TD: 7.8 mm posterior – 15.04%; TD: 7.3 mm anterior – 19.22%). In the mediolateral direction, absolute percentage changes at the ankle were highest (CP range: 13–56%; TD range: 12–65%). Absolute percentage change for coronal moments with error applied mediolaterally were larger to absolute percentage changes for sagittal moments with error applied anteroposterially (Tables 1 and 2). However, the impact of mediolateral error in the coronal plane was not as obvious visually on the kinetic profiles as the impact of anteroposterior error in the sagittal plane (Appendices 5 and 10). This is due to the lower moment values in the coronal plane whereby a similar or greater percentage change would be more difficult to see graphically. The resultant changes in GDI-Kinetic in the mediolateral direction were small and below the CMID suggesting that the associated error would not be considered clinically significant.

It was felt that the use of statistical analysis would be inappropriate as the displacement of the CoP produced changes in kinetics that were predictable in direction, therefore the results of this sensitivity analysis were instead examined from a clinical perspective. A clinical interpretation of our data suggested CoP location error above 7.3 mm may be concerning when assessing children with TD in an anteroposterior direction. Depending on the clinical population being assessed (e.g. children with CP) this threshold for error could be extended to 12 mm as no changes were demonstrated for children with CP at or below this increment. In addition, while absolute percentage differences were high at some increments, a substantial percentage difference may still be clinically acceptable as determined by the GDI-Kinetic. To conclude, the findings of this study highlight the need for laboratories to consider the thresholds currently used for CoP location error, which may then help guide the quality assurance procedure.

Declaration of Competing Interest

None of the authors had any financial or personal conflict of interest with regard to this study.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.05.034.

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