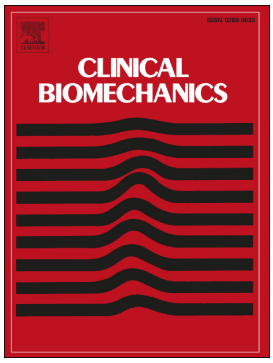

How multi segmental patterns deviate from normal in spastic diplegia

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How multi segmental patterns deviate from normal in spastic diplegia

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Highlights

- Principal Movements characterize gait patterns in children with Cerebral Palsy.
- Children with Cerebral Palsy show higher movement dimensionality than controls.
- The interaction among main and secondary components outlines compensatory patterns.
- Principal Movements provide an immediate measure of multi-joint kinematics.

ABSTRACT

Background

The relationship between gait features and coordination in children with Cerebral Palsy is not sufficiently analyzed yet. Principal Component Analysis can help in understanding motion patterns decomposing movement into its fundamental components (Principal Movements). This study aims at quantitatively characterizing the functional connections between multi-joint gait patterns in Cerebral Palsy.

Methods

65 children with spastic diplegia aged 10.6 (SD 3.7) years participated in standardized gait analysis trials; 31 typically developing adolescents aged 13.6 (4.4) years were also tested. To determine if posture affects gait patterns, patients were split into Crouch and knee Hyperextension group according to knee flexion angle at standing. 3D coordinates of hips, knees, ankles, metatarsal joints, pelvis and shoulders were submitted to Principal Component Analysis.

Findings

Four Principal Movements accounted for 99% of global variance; components 1-3 explained major sagittal patterns, components 4-5 referred to movements on frontal plane and component 6 to additional movement refinements. Dimensionality was higher in patients than in controls ($p<0.01$), and the Crouch group significantly differed from controls in the application of components 1 and 4-6 ($p<0.05$), while the knee Hyperextension group in components 1-2 and 5 ($p<0.05$).

Interpretation

Compensatory strategies of children with Cerebral Palsy (interactions between main and secondary movement patterns), were objectively determined. Principal Movements can reduce the effort in interpreting gait reports, providing an immediate and quantitative picture of the connections between movement components.

KEY WORDS: Cerebral Palsy, Principal Component Analysis, Gait Analysis, Principal Movements.

1 INTRODUCTION

Walking is one of the most compromised functions in children with Cerebral Palsy (CP). While the gait of patients with CP has been found to be more heterogeneous than that of healthy children, certain parameters extracted from classical gait analysis are considered typical features of CP locomotion: shorter strides, slower walking speed, reduced joints range of motion, altered ankle movement (Piccinini et al., 2011; Russell et al., 2011); typical joint kinematics are also present in the most common forms like diplegia and hemiplegia.

In clinical practice, the identification of these gait strategies is very useful in the evaluation of the treatment outcomes as well as in the therapeutic decision-making process. While in literature there are many studies presenting the assessment of specific features at different joints level, and their alterations with respect to a normally developed control group (Brégou Bourgeois et al., 2014; Russell et al., 2011; Sangeux and Armand, 2015; Sutherland and Davids, 1993), little is known about the coordinative skills that characterize how the relative motion among body segments or between body segments and the environment is controlled. Further, the relationship between typical features and the coordination of different body segments has not been sufficiently analyzed yet in CP.

Principal Component Analysis (PCA) has emerged in recent years as a data analysis technique that can help in understanding motion patterns through decomposing movements into their fundamental motor structures, called Principal Movements (PMs) (Daffertshofer et al., 2004; Federolf et al., 2012, 2013; Troje, 2002). This powerful

technique allows to encapsulate a large amount of information regarding multi-segmental motion in a reduced number of variables.

To the best of our knwoledge, there are no studies using PCA to investigate Principal Movements patterns in CP. Previous works used PCA to analyze gait features of individuals with CP, to define synthetic gait indexes based on the comparison with the healthy populations (Schutte et al., 2000), or to unveil the inner structure of a complex dataset of arbitrarily-selected kinematic (Carriero et al., 2009) or electromyographic (Lauer et al., 2005) parameters.

Thus, the major aim of the present study is to quantitatively characterize the functional connections between multi-joint patterns in CP gait, starting from a group of subjects with spastic diplegia. This subset of CP population allows to investigate a symmetrically impaired pattern in people able to walk without assisting aids. We hypothesize that: (i) differences with respect to healthy children could appear in terms of higher movement dimensionality, since the pathological function impairment might induce compensatory movement strategies; (ii) typical diplegic CP features like knee flexion angle while standing might be related to deviations in the shape and timing of kinematics gait patterns with respect to normalcy. This analysis would allow a better understanding of the motor patterns in CP, providing the clinicians with an objective tool to investigate functional behaviors of their patients.

2 METHODS

2.1 PARTICIPANTS

A sample of 65 children (38 males, 27 females) with spastic diplegia (CP) aged 10.6 (SD 3.7) years was included in the study. The patients were selected within the IRCCS San Raffele Pisana Hospital (Rome, Italy) gait database in a retrospective analysis; 17 out of 65 participants reported a Gross Motor Function Classification Scale (CMFCS, Palisano et al., 1997) level I, 23 level II, 16 level III and 9 level IV. The inclusion criteria were: (a) diagnosis of diplegic CP, GMFCS Level I-IV; (b) no previous orthopedic surgery on any of the lower limb joints; (c) no botulinum toxin injection into the lower limbs within 6 months prior to the assessment, or casts on these levels; (d) no previous selective dorsal rhizotomy or implantation of a Baclofen pump; (e) were independent ambulators without the assistance of aids.

A group of 31 physically healthy Typically Developing (TD) adolescents (19 males, 12 female) aged 13.6 (4.4) years (Table 1) were also tested to obtain the reference data set. Selection criteria for this group included no prior history of cardiovascular, neurological or musculoskeletal disorders. They exhibited a normal range of motion and normal muscle strength, and did not have any apparent postural and motor deficits.

The study was approved by the Hospital Ethics Committee (n. 4/17) in accordance with the Helsinki Declaration of 1975. All participants were volunteers and their parents or legal guardians gave their written consent to the children's participation.

2.2 PROCEDURES AND DATA COLLECTION

Participants were involved in standardized gait analysis trials: they were recorded at a sampling frequency of 100 Hz by means of an optoelectronic motion capture system consisting of 12 cameras (Elite2002, BTS SpA, Milano, Italy) while walking barefooted along a 10-m walkway at self-selected comfortable speed; 21 passive plastic markers

(diameter: 15 mm) were placed on the body according to Davis' protocol (Davis et al., 1991). Once verified the consistency of the five recorded trials, one was selected as representative of participant's gait (Gage, 1993). The rest between trials was at least two minutes.

Before gait analysis, a standing trial was also recorded for each child with CP to determine the standing posture; the participants were instructed to maintain an upright standing position for 5 seconds with open eyes focusing on a 6 cm black circle positioned at the individual line of vision at a distance of 1.5 m. Arms were at their sides and feet were in a comfortable position.

2.3 DATA ANALYSIS

Custom Matlab (Mathworks Inc., USA) software was used for most of data processing. The dedicated software for gait analysis report realization (Gait Eliclinic, BTS, IT) provided the computation of internal joint centres of rotation, ICoR (according to the Davis biomechanical model). A set of 14 points containing the instantaneous raw three-dimensional position of ICoR of hips, knees, ankles and metatarsal joints, and the position of right and left acromion, antero-superior iliac spines, c7 and sacrum were extracted.

Raw coordinates were filtered with a 15 Hz low-pass, zero-lag, 2nd order Butterworth filter. Consecutive heel-strikes were located using the BTS Elite Software; tracks over the stride cycles were then interpolated to 100 frames. All coordinates were expressed in a new right-handed orthogonal reference system, whose origin was at the midpoint between the two ASIS, the *y*-axis was vertical and pointing upwards, the *z*-axis was

horizontal and oriented as the vector between the two ASIS, pointing to the right; the *x*-axis was the cross product of *z* and *y*, pointing forward.

The position of the whole marker set at a given time point was labelled as a "posture" vector. Within each trial, the average posture ($\mathbf{P_{mean}}$, i.e. coordinates algebraic mean) was subtracted by each posture vector and normalized by the average Euclidean norm of the posture vectors of every subject. We refer to this procedure as "postures registration".

2.3.1 Global movement dimensionality

A first PCA was performed separately for each participant on the resulting postures matrices ($\mathbf{P}_i$, sized [(14 joint centers · 3 coordinates) × 100 frames], where the subscript *i* refers to the *i*-th subject). The variance explained by the eigenvalue of each Principal Component (PC) was expressed as a percent of the total variance. Movement dimensionality was quantified in terms of the Residual Variance (RV), i.e. the relative amount of variance in the PCs of order higher than 4, which was considered the residual pattern (Verrel et al., 2009):

$$RV = \sum_{n=5}^{N} Explained\ variance_n$$

where *n* is the order of the PC and *N* their total number. Higher values of RV indicated higher postural dimensionality in the sense that more patterns of movement were utilized in gait. The number of 4 retained PCs was chosen as the lowest number of components explaining on average 99% of variance for all groups.

2.3.2 Principal Movements

Subsequently, the posture matrices of all subjects were combined in a global matrix $\mathbf{P_{global}}$ [(14 joint centers ·3 coordinates) × (100 frames · (65+31) subjects)]. A PCA was performed on the covariance matrix of $\mathbf{P_{global}}$, obtaining a set of orthogonal eigenvectors (the Principal Components), that will be referred to as *eigenpostures* ($\mathbf{ep_n}$), where the subscript *n* denotes the *n*-th component. PCA also returns a scores matrix **W**, constituted by a series of columns ($\mathbf{w_n}$) representing the *weighting* of each PC during the step cycle. Weightings quantify the timing and intensity of the movement components expressed by each $\mathbf{ep_n}$. The multiplication of a weighting vector by the correspondent eigenposture, summed to the mean posture ($\mathbf{ep_n} \times \mathbf{w_n} + \mathbf{P_{mean}}$), allows to project each eigenposture back into the original coordinate system. This procedure enables to visually resynthesize multi-segmental modules, that for this reason were defined as Principal Movements (PMs) (Federolf, 2015). PMs were ranked on the basis of their variance; to provide a characterization of CP gait patterns, PMs that accounted up to 99.9% of the global variance were described.

2.3.3 Comparison of Principal Movements between individuals

Combining all the trials in a single matrix, the obtained PMs were the same for all participants and this prevents a direct comparison of movement patterns between them. To detect differences between groups, the weightings of each component were considered. As a measure of the impact of each PM on the overall motion, we introduced the Relative Amplitude (RA), computed for the *p*-th participant and *n*-th PM as the ratio between the amplitude (i.e. absolute area below the $\boldsymbol{w_n}$ curve) of the *n*-th weighting (multiplied by the corresponding eigenvalue) and the sum of the areas (weighted as well) subtended by the weightings of all PCs:

$$Relative\ Amplitude_{n,p} = \frac{\lambda_n \sum_{t=1}^{100} |\boldsymbol{w}_{n.p,t}|}{\sum_{n=1}^{N} \lambda_n \cdot \left(\sum_{t=1}^{100} |\boldsymbol{w}_{n,p,t}|\right)}$$

where t is the considered time frame and λ_n the n-th eigenvalue returned by the PCA.

Many children with spastic diplegia are characterized by a crouch gait (abnormal knee flexion) condition. Thus, to assess if standing posture can affect the nature of gait patterns, the CP group was divided considering the average knee flexion angle in the standing trial.

Patients were assigned to knee flexion (KF) group, if their knee flexion angles at standing were higher than 5 degrees for both limbs, or to knee hyperextension group (KE) if their knee flexion angles were lower than -5 degrees. The entire data processing flow is portrayed in Figure 1.

2.4 Statistical analysis

Assumptions of normality was verified for each variable using the Jarque-Bera test. Data are presented as means and standard deviations. Differences in anthropometrics between groups were tested with unpaired Students' t-tests. For the Residual Variance and the Relative Amplitude of each PM, a 1-way ANOVA was performed to test the difference between KF, KE and TD groups. Where appropriate, post-hoc Tukey Honest Significant Difference tests were applied. The significance level was set at α = 0.05 for all analyses.

3 Results

Walking speed was 0.716 (0.205) m/s in children with CP and 0.984 (0.185) m/s in the TD group. The percentage of variance explained by each PC is reported in Figure 2: on

average, the first four PMs accounted for more than 99% of the global variance (Table 2). Table 2 also provides a description of the first six PMs, that elucidates the stick-diagrams and the time course of weightings illustrated by Figure 3. In particular, the first three PMs expressed major patterns on the sagittal plane, while PM4 and PM5 introduced lateral movements that can be observed mainly on the frontal plane. PM6 referred to a further refinement of movement regarding pelvic tilt.

The period of PM1 and PM3 was one stride, while that of PM2 one step (twice per stride). The periodicity of PM4-6 was highly variable according to individual differences.

Patients were classified according to their knee-standing angle: 34 (52.4%) were assigned to the KF group, 9 (13.8%) to the KE group, 15 (23.6%) had a different (asymmetric) behavior on the two knees. Asymmetric patients were not further analyzed.

Residual Variance was significantly higher ($p<0.01$) in KF (1.30, SD 0.96) and KE (1.58, SD 0.98) than in TD (0.81, SD 0.27). Differences in Relative Amplitude were found for all the first six PMs (Table 3). In particular, KF was significantly different from TD in four PMs (PM1 and PM4-6), and KE in PM1-2 and PM5.

4 DISCUSSION

The major novelty of the present work is the characterization of gait-related fundamental motor modules in a group of children with diplegia. Not only we objectively determined differences from the normal pattern, as already largely shown in previous literature (Rodda et al., 2004; Sangeux et al., 2015), but we also identified the

compensatory strategies the patients arranged to adjust the impaired motor components, i.e. the interactions between main and secondary movement strategies.

PCA was already applied to CP by different Authors (Carriero et al., 2009; Lauer et al., 2005; Schutte et al., 2000), but the purpose of these studies was to assess the structure of a dataset of traditional gait variables in order to provide a quantitative classification or normalcy indexes of patients based on PCs. Rather, in the present paper we present a characterization of global movement patterns on a 3D motion data-driven perspective.

The cumulative variance explained by the first four PCs was more than 99% in both groups, while the first PM alone accounted for 89% of global variance in TD. These values are slightly higher compared to previous PCA-based investigations on gait, where PM1 ranged from 84% to 86% and the sum of PM1-4 was 90-98% (Daffertshofer et al., 2004; Federolf et al., 2012; Troje, 2002). This was due to the smaller marker-set we adopted, which did not include upper limbs, and thus reduced the global movement dimensionality. In the current study, a comprehensive analysis of trunk and lower limbs movement was still fully granted by the Davis protocol (Davis et al., 1991).

4.1 MULTIPLE SUBJECTS COMPARISON

A direct numeric comparison with adult healthy gait patterns already described in literature is not allowed, since different recording equipment and protocols necessarily change the shape of the extracted components. However, the overall morphology of the main gait patterns described by PM1 to PM3 were consistent with previous investigations. In general, high-order PMs represent adjustments of these first basic movement components (Federolf et al., 2012). After the first PCA, which yielded a global picture of the movement complexity, expressed by the RV, in this investigation we

performed a second, unique PCA on the whole database. That is, we computed the invariant feature of motion (PMs) common to all (KF, KE and TD) participants. This way it was possible to directly compare PMs in terms of the Relative Amplitude, which is subject specific instead.

In this sense, the inclusion of a TD control group in this analysis appeared essential: it allowed for the assessment of how movement components typical of human bipedal gait apply to a specific pathological condition. Further, this methodological procedure enables the comparison of results related to other pathologies, just substituting the CP data with those belonging to a different population.

The control group were not exactly matched in age with CP. However, the performed analysis focuses on the synergies of landmarks relative movements, and it is insensitive to body size mismatches; more importantly, there are evidences that gait matures to an adult-like pattern by the age of 7-9 years (Chester et al., 2006; Ganley and Powers, 2005; Kliegman et al., 2015), and that the related biomechanical variables are similar among children and adolescents at intermediate walking speeds (Cavagna et al., 1983). Moreover, while speed differences among groups are reported to produce a relevant impact on joint angles (Perry and Burnfield, 2010), at present, there are no published evidences that a walking speed delta of about 0.25 m/s provokes changes in PC weightings.

It has to be noticed that while in high-order PMs the magnitude of RA can be low, the relative difference between groups was in some cases highly significant, providing a measure of the extent to which a certain module is or not activated in pathological gait.

4.2 Residual Variance and weightings

The amount of Residual Variance was substantially aligned with that measured by Verrel et al. (2009) in adults and was, as expected, significantly higher in CP groups. This is a mark of higher movement dimensionality; in other words, in CP more PMs were necessary to fully characterize the global gait patterns (Figure 5). This finding reinforces the hypothesis that the movements described by high-order PMs (in this case, from PM4) represent compensatory patters that are applied with a high level of individual specificity by each patient. Such inter-individual variability can be also appreciated in the time course of weightings of these PMs. A more sophisticated analysis of these curves could reveal differences between groups of patients in terms of periodicity and dynamic application of a selected PM.

4.3 Characterization of Principal Movements in CP

As a general trend, while the RA of PM1 was higher in TD participants, the Relative Amplitude of high-orders PMs was necessarily increased in the two CP groups. In this regard, we can observe the global way a patient organizes functional features of gait by assessing how high-order PMs act as error-correction strategies that compensate movement impairments encountered in the main healthy gait patterns.

A body of evidence supports the notion that children with CP exceed in hip flexion, due to iliopsoas spasticity, and show a consequently reduced stride length (Brégou Bourgeois et al., 2014; Rodda et al., 2004). Besides outlining a more stable and less dimensional global pattern, the significantly higher RA of PM1 found in TD group (difference of about 8%) is representative of this motion pattern; further, the reduced hip extension range of motion is related to an excessive anterior pelvic tilt, expressed by PM6. Coherently, in PM6 the Relative Amplitude was four times higher in children with

CP than in TD. Movements described by this motor module also involve trunk flexion/extension, whose range was increased in CP.

RA differences in PM2 accounted for the well-documented augmented center-of-mass vertical displacements due to increased knee flexion and hyperextension in CP, especially in the HE group. The latter is caused by a general quadriceps weakness (Rodda and Graham, 2001), and it is associated to excessive knee flexion related to the higher RA in PM5 showed by both CP groups. Interestingly, on the sagittal plane these ankle and knee patterns are accompanied by an increase in foot rotation, trunk inclination and pelvic obliquity (see Table 2). The latter is commonly attributed to an alteration in abduction/ adduction activity as expressed in KF by PM4. This is in accordance with the increased step width and consequent larger lateral center-of-mass displacements observed in CP patients as a result of a balance maintenance strategy (Rodda et al., 2004). Finally, the augmented ankle rotation pattern of PM5 is coherently accompanied by a hip rotation pattern, expressed by PM6.

Traditionally, most of the connections between the aforementioned movement features were outlined through the examination of gait analysis reports conducted by an expert clinician or biomechanists. Instead, we claim that PMs provide an immediate picture of the functional structure of multi-joint/ multi-plane kinematics. This is objectively quantified and does not necessarily require the interpretation of an expert operator.

In addition, we proved that different postural arrangement at standing (KF vs. KE) reflected different degrees of alterations of gait patterns in some PMs with respect to normal gait. This can spread light on how a postural alteration produces specific adjustments in the walking action which translates in compensatory patterns.

It is worth remembering that the results of the current study come from a Spastic Diplegia sample and do not necessarily apply to other CP populations. However, the inclusion of hemiplegic subjects in analogous future investigations should be carefully considered in terms of the impaired laterality side. Lastly, a longitudinal assessment of how motor patterns changes in the patients' follow-up is advisable for future investigations.

5 CONCLUSIONS

The gait kinematics of children with spastic diplegia was decomposed into its fundamental movement components, and the motor patterns different from healthy condition and compromised by pathology were quantitatively detected. The case of PM5 is representative of the capability of such analysis of identifying interrelated compensatory joint motion patterns. In other words, quantifying the Relative Amplitude of a PM between different groups, or in the same individual over time, enables to readily detect a change in multi-joints synergies. This kind of analysis was not possible considering arbitrary selected variables or time-series. Even though the inspection of joint angles kinematics remains extremely useful in clinical setting to design intervention procedures, this PCA-based technique adds a quantitative perspective on the coordination patterns affected by spastic diplegia.

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TABLES

Table 1. Participants' age and anthropometrics, presented as groups mean (SD).

	Unit	CP	TD
n	-	65	31
Age	Years	10.6 (3.7)	13.6 (4.4) *
Weight	kg	40.2 (16.7)	49.9 (13.8) *
Height	m	1.38 (0.19)	1.53 (0.15) *
BMI	$kg \cdot m^{-2}$	20.1 (4.7)	20.6 (2.8)

CP: Cerebral Palsy group; TD: Typically Developing (control group). *: significant difference between groups, $p<0.01$ (Student's t-test).

Table 2: Principal Movements (PMs) characterization. Cumulative variance expressed by PMs, expressed as groups mean (SD), is accompanied by a concise description of the related multi-joint movement pattern.

PM	Cumulative explained variance (%)		Main plane of motion	Description	Involved joint movements
	CP	TD			
1	83.79 (7.18)	88.92 (2.13)	Sagittal	Posture variation due to anterior-posterior leg swing	Hip flexion/extension
2	93.64 (2.31)	95.03 (1.11)	Sagittal	Synchronous flexion-extension of both knees with an in-phase vertical movement of the upper body	Knee flexion/extension
3	98.71 (0.84)	99.19 (0.27)	Sagittal and frontal	Asynchronous knees flexion with an in-phase medial shift of the upper body (and thus body weight) onto the stance leg	Hip internal/external rotation Knee flexion Ankle dorsi/plantar flexion
4	99.62 (0.27)	99.89 (0.10)	Frontal	In-phase hip adduction with trunk inclination	Hip abduction/adduction
5	99.83 (0.14)	99.95 (0.04)	Frontal	Pelvic obliquity, trunk inclination and slight knee flexion on the same side (typical compensatory pattern of PCI)	Trunk inclination Pelvic obliquity Knee flexion/extension Ankle dorsi/plantar flexion
6	99.91 (0.07)	99.98 (0.02)	Sagittal	Pelvic tilt and corresponding trunk flexion/extension	Trunk flexion/extension Pelvic tilt Hip internal/external rotation

CP: Cerebral Palsy group; TD: Typically Developing (control group).

Table 3: Relative Amplitude divided by group and Principal Movement (PM).

PM	Relative Amplitude (%)			p
	CP children		TD	
	KF	KE		
PM1	82.46 (8.46) *	81.65 (8.74) #	89.37 (2.01)	0.0001
PM2	6.02 (2.29)	7.09 (1.95) #	5.03 (1.5)	0.0169
PM3	6.62 (5.13)	7.47 (4.8)	4.48 (1.14)	0.0437
PM4	2.05 (3.26) *	1.22 (1.30)	0.58 (0.36)	0.0401
PM5	1.7 (1.58) *	1.71 (1.94) #	0.29 (0.22)	< 0.0001
PM6	1.14 (1.29) *	0.86 (0.78)	0.24 (0.24)	0.0009

p: 1-way ANOVA. Post-hoc comparisons: * significant difference KF vs. TD, # significant difference KE vs. TD. CP: Cerebral Palsy; KF: knee flexed (>5°) at standing; KE: knee hyperextended (<5°) at standing; TD: Control Group.

FIGURE LEGENDS

Figure 1: data analysis workflow diagram.

Figure 2: variance explained (mean + SD) by the first 8 Principal Components in the control group (TD, white) and in children with Cerebral Palsy (CP, gray).

Figure 3: weightings (left column) and stick diagrams (right columns) depicting the motor patterns related to the first six Principal Movements (PMs). Gray lines refer to Cerebral Palsy children, while the shaded area is drawn between healthy controls' confidence intervals. Gray arrows indicate the main direction of multi-joint movements, labels the main joints involved in each component; white markers represent the joints involved in each component.

Stick diagrams are obtained starting from the average posture and resynthesizing each component in the maximum and minimum weighting time point.

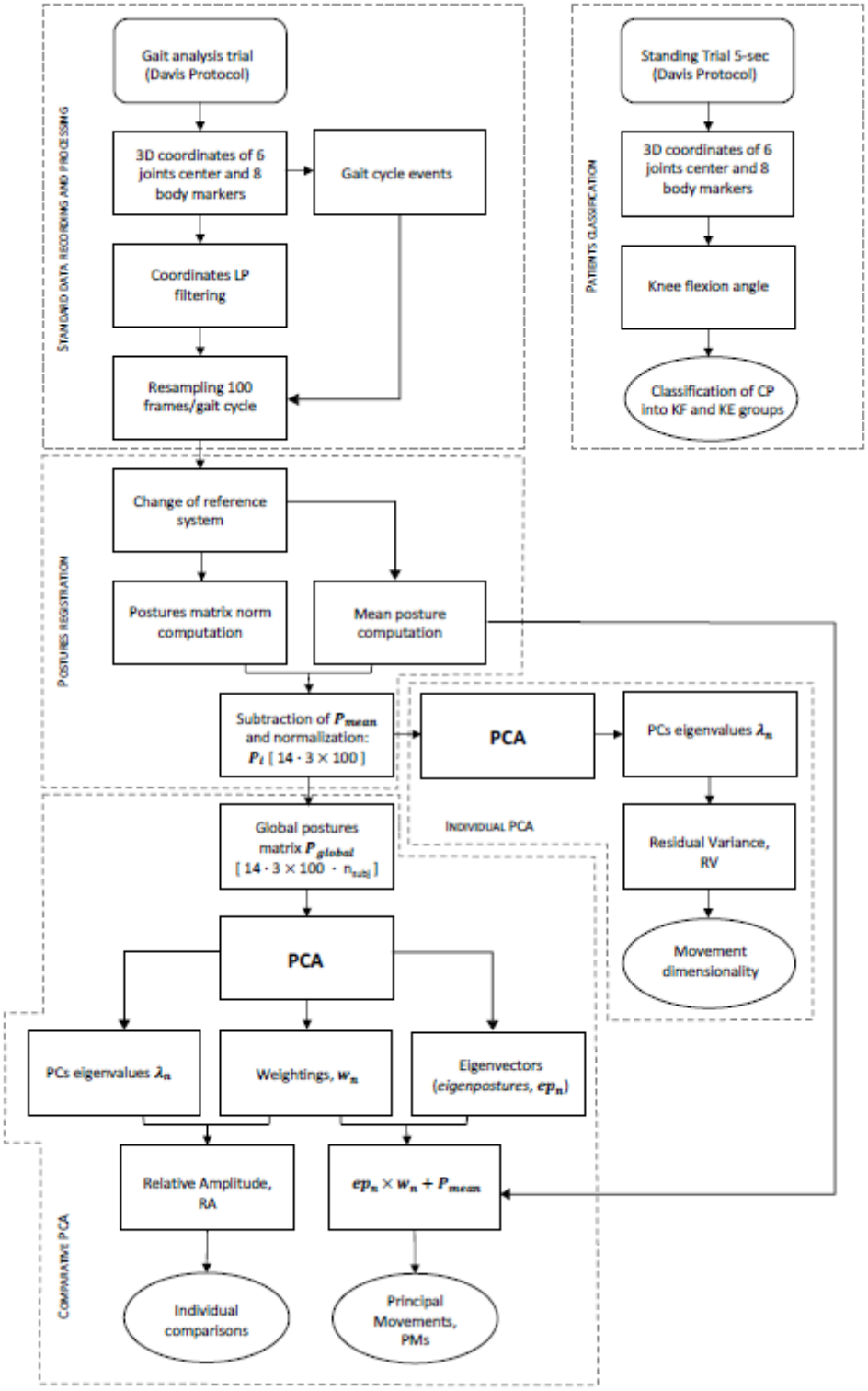

Fig. 1

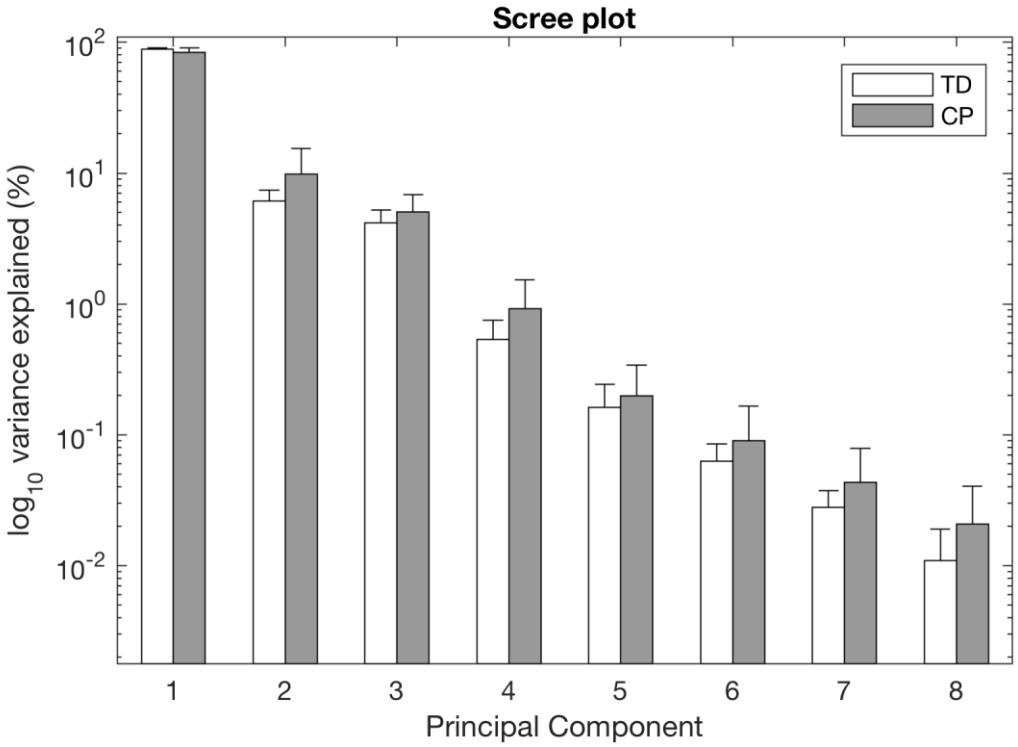

Fig. 2

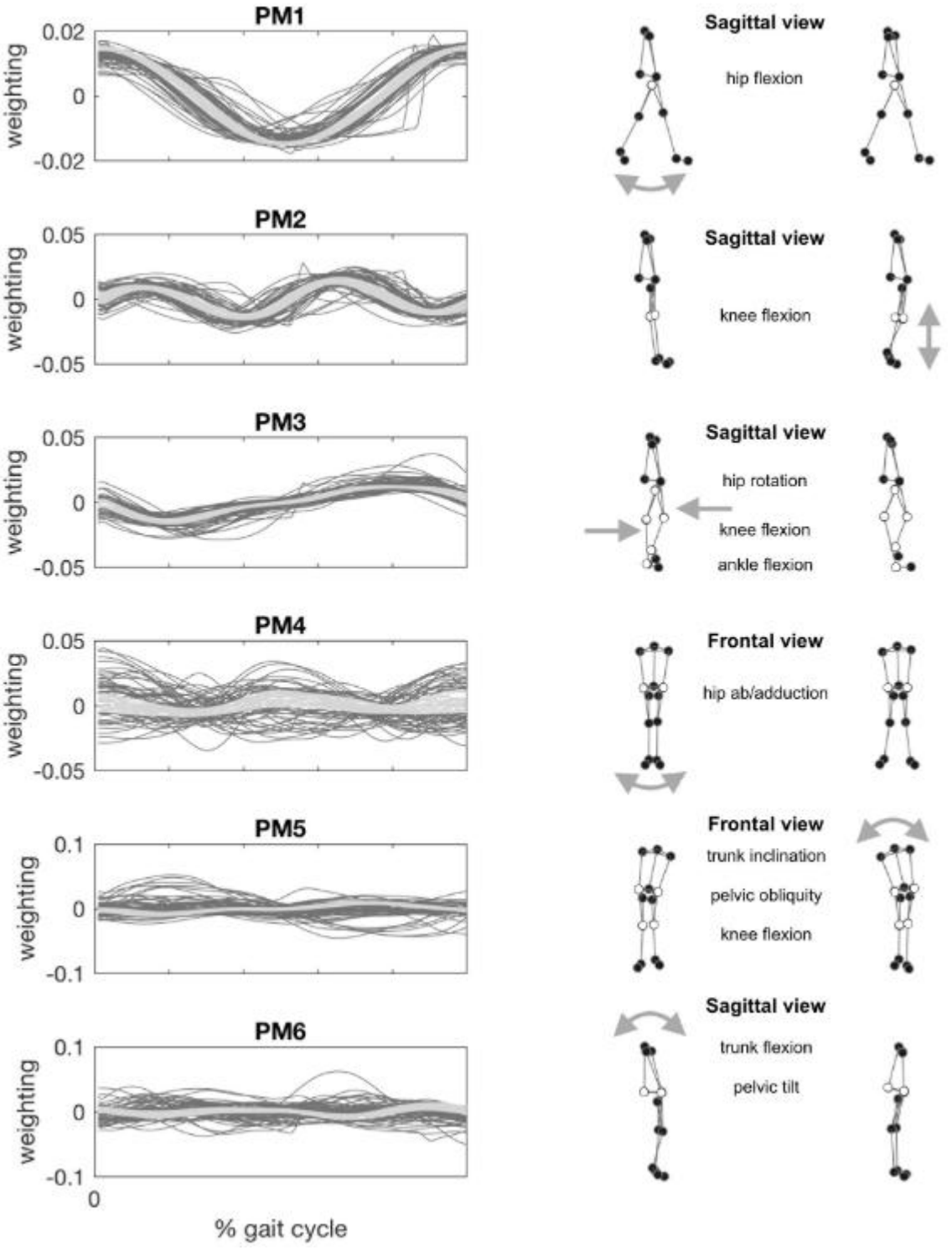
PM1
weighting
0.02
0
-0.02
Sagittal view
hip flexion
PM2
weighting
0.05
0
-0.05
Sagittal view
knee flexion
PM3
weighting
0.05
0
-0.05
Sagittal view
hip rotation
knee flexion
ankle flexion
PM4
weighting
0.05
0
-0.05
Frontal view
hip ab/adduction
PM5
weighting
0.1
0
-0.1
Frontal view
trunk inclination
pelvic obliquity
knee flexion
PM6
weighting
0.1
0
-0.1
Sagittal view
trunk flexion
pelvic tilt
0
% gait cycle

Fig. 3