In: Orthopedic Management of Children with Cerebral Palsy ISBN: 978-1-63483-318-9
Editors: Federico Canavese and Jacques Deslandes

Chapter 18

KINEMATIC DEVIATIONS IN CHILDREN WITH CEREBRAL PALSY

Morgan Sangeux[1,2,3,*] and Stephane Armand[4]
[1]The Royal Children's Hospital, Melbourne Australia
[2]Murdoch Childrens Research Institute, Melbourne Australia
[3]The University of Melbourne, Melbourne Australia
[4]Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals and Geneva University, Switzerland

ABSTRACT

In gait analysis, a large portion of the work consists in finding the underlying causes of the abnormal movement observed during walking. The patient's kinematics of walking is compared to that of typically developed children and the deviations are further analysed. Over the years, clinicians have observed multiple-joints kinematics deviations that were frequent in children with cerebral palsy and devised gait patterns in order to group patients and support management algorithms. However, the gait patterns are broad tools and cannot render the complexity and varying degrees of impairments seen in children with cerebral palsy. To devise individualised management plan, clinicians prefer to list single joint kinematic deviations and to link these with underlying impairments. This chapter will present the main clinical gait patterns for children with unilateral or bilateral spastic palsy in the first part and the principal single joint/plane kinematic deviations together with their associated impairments in the second part.

Keywords: kinematic deviations; children cerebral palsy; gait

[*] Corresponding author: Morgan Sangeux, PhD Murdoch Childrens Research Institute, 50 Flemington Road, Parkville VIC 3052, Australia; E-mail: morgan.sangeux@gmail.com

KEY POINTS

- Clinical gait analysis is an excellent tool to identify as best as possible gait deviations and possible linked impairments.
- Gait patterns are used to provide a classification system able to assist with communication and management for patients with unilateral or bilateral spastic cerebral palsy.
- Establishing the links between kinematic deviations and impairments is key to understand gait impairments.

18.1. INTRODUCTION

Instrumented gait analysis provides detailed information on the kinematics of the lower limb during gait. A typical gait analysis requires to analyse and interpret the kinematics of five segments or joints (trunk, pelvis, hip, knee and ankle/foot) in three planes. These data are essential to plan the best therapeutic strategy for the patients and evaluate treatment outcomes.

Clinical interpretation based on instrumented gait analysis may be split in two phases, first identify where and how the kinematics of the patient differs from that of normal subjects, then find the skeletal deformities or neuromuscular problems, called impairments, that are likely to be the cause of the deviation(s) observed. It is important to keep in mind that kinematic deviations may result from two reasons: (i) it is related to a primary impairment that affect the capacity of the patient to walk normally or (ii) it is a secondary, compensatory, mechanism that the patient adopt in relation to some primary problems. The difficulty of gait analysis interpretation is to differentiate between these two reasons in order to report, and address, the primary problems. An additional difficulty is that the relationships between impairments and kinematic deviations are not bijective. The same impairment may result in a range of kinematic deviations and the same kinematic deviation may originate from a range of impairments. The causal relationship between a kinematic deviation and a particular impairment is therefore uncertain without additional evidence.

Evidences may be provided by the presence, or absence, of other kinematic deviation(s) related to the same impairment, kinetics data, electromyography data, physical examination and medical imaging data.

Gait of patients with cerebral palsy is often classified in different patterns. However, the term pattern may refer to slightly different concepts in the literature and need to be clarified.

Pattern may refer to the movement at one joint and plane or the simultaneous movement across several joints and/or planes. It may encompass the notion of similarity but may also refer to a feature frequently seen with varying degree, rather than identical, among a group of subjects.

It may be that the only strict “gait pattern” is the normal gait pattern: a multiple-joints, multiple-planes movement similar in all human beings without neuro-musculo-skeletal problems. Such inclusive notion of pattern will seldom be found among patients as they suffer from various impairments with varying degree of disturbance.

Authors have devised clinical gait patterns for features frequently found in patients with cerebral palsy. The purpose was to provide a common language and assist in the development of management algorithms.

The patterns mostly relate to the sagittal plane and mostly describe patterns that includes multiple joints. These patterns tried to identify and group frequent kinematic deviations across multiple joints in order to propose management algorithms to address the underlying problems.

The first part of this chapter elaborates on the most common clinical gait patterns in children with cerebral palsy while the second part focuses on the most common single joint/ plane kinematic deviations observed in children with cerebral palsy and the impairments they may be associated with.

18.2. Gait Patterns to Assist with Management

Gait patterns were designed for patients with unilateral or bilateral spastic cerebral palsy. The intention of the gait patterns were to provide a classification system able to assist with communication and management. Although qualitative and expert based, the most popular classifications were derived from quantitative kinematics data.

Gait Patterns in Unilateral Spastic Cerebral Palsy

The first gait pattern classification system for unilateral spastic cerebral palsy originated from Winter et al. [1]. The classification system was based on the sagittal plane kinematics at the ankle, knee, hip and pelvis joints and included four types that represents increasing degree of gait disturbance. The key feature in type 1 patients is a drop foot in late swing followed by an absent first rocker in early stance. The associated impairment may be a combination of overactive plantarflexors and weak tibialis anterior muscle or/and an impaired selective motor control. Clinical management only include a hinge AFO to prevent sustained plantarflexion in swing. Type 2 patients present with drop foot and reduced dorsiflexion in stance. Additional impairment compare to type 1 may be a contracture of the plantarflexors. Clinical management may include lengthening of the gastroc-soleus complex. Type 3 patients present with the features of type 1 and 2 and increased knee flexion at initial contact and/or sustained during stance. Reduced and or delayed knee flexion in swing may also be present. Additional impairments to the types 1-2 patients include spasticity or contracture of the hamstring or rectus muscles and clinical management include the appropriate treatment for these muscles. Finally, type 4 patients present with deviations at the hip, reduced extension, and pelvis, increased anterior tilt, on top of types 1-3 deviations. Management for type 4 patients require treatment for the muscles crossing the ankle, knee and hip joints [2].

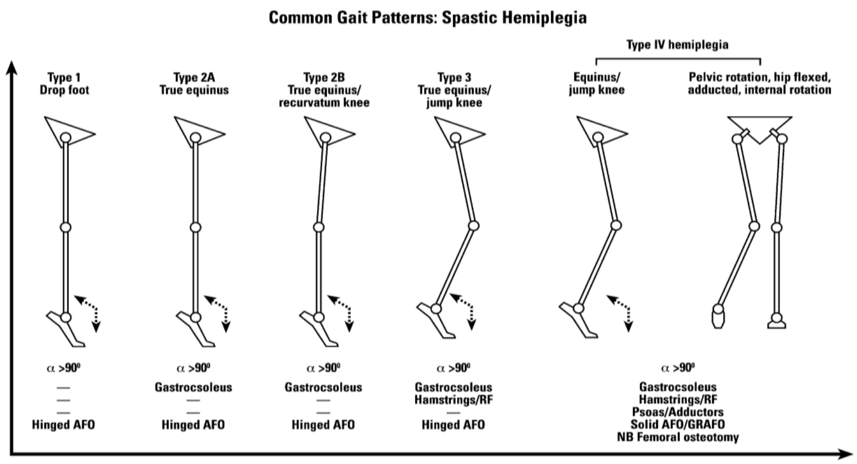
In 2001, Rodda and Graham refined Winter’s classification to include patients with hyperextension at the knee and transverse plane deviations at the hip [3]. The authors provided a schematic which describes the main kinematic deviations and the management algorithms (Figure 1).

Gait Patterns in Bilateral Spastic Cerebral Palsy

Rodda et al. [3, 4], described a classification based on sagittal plane kinematics mostly at the ankle and knee joints for patients with bilateral spastic cerebral palsy. The classification was based on earlier work by Rang et al. [5], Sutherland and Davids [6] and Miller et al. [7].

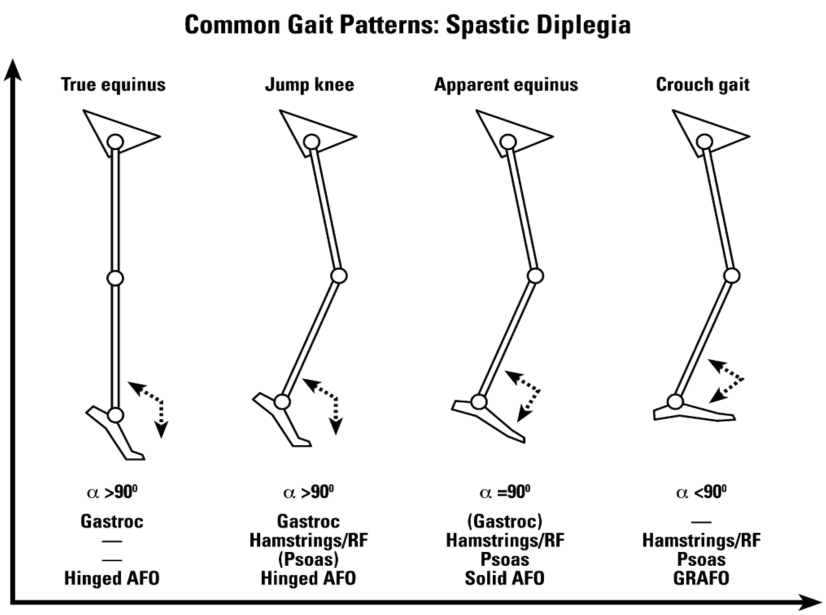
The Rodda classification described five groups: mild gait, true equinus, jump gait, apparent equinus and crouch gait (Figure 2).

Patients in mild gait do not present any significant deviation in the sagittal plane but may present deviations in other planes.



Reprinted from European Journal of Neurology.

Figure 1. Gait patterns and management algorithm in spastic hemiplegia [3].



Reprinted from European Journal of Neurology.

Figure 2. Gait patterns and management algorithm in spastic diplegia [3].

Patients in true equinus present excessive plantarflexion in mid-stance. Patients in jump gait present excessive plantarflexion and knee flexion in mid-stance while patients in apparent equinus present normal ankle kinematics but knee flexion in mid-stance.

Last, patients in crouch gait present excessive dorsiflexion and knee flexion in mid-stance. The classification in five groups applies to the limb but the authors recognised that the two limbs may present different level of involvement and introduced an asymmetric group when the two limbs belong to two different classifications. Rodda et al. derived a management algorithm which specifies the dominant muscle groups to be targeted for treatment of spasticity or contracture and includes prescription of orthotics (Figure 2).

The classification systems presented above were clinically driven and focused on kinematic deviations frequently seen in the clinical setting.

As such, they correspond well to the clinicians' experience and have been utilised in clinical research to describe cohorts' characteristics. However, the systematic review by Dobson et al. deplored the lack of quantitative guidelines for the construction of the classifications and their validity from the statistical point of view [8]. Several authors tried to build classifications using both quantitative data and statistical criteria. The inherent disadvantage of such study is that the statistical process removes the direct correlation with joints function and limits clinical understanding and use.

Most statistically driven study assist clinical understanding by projecting the various group means onto the kinematic graphs of interest e.g., [9-11].

Recent works proposed a quantitative index to classify the sagittal gait pattern according to Rodda's classification and validated its statistical properties post-hoc [12]. The results showed that clinical and statistical classifications in the sagittal plane were similar and were related to physical examination measurements of the plantarflexors.

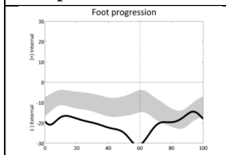
In most studies, patients present a continuum of deviations rather than well delineated groups. This highlight the specificity of each patient who may present a different list of impairments, and each with varying degree of involvement and asymmetry between the two limbs. The patient or limb centred gait pattern classifications described above support broad management algorithms while clinical decision making is impairment centred. Impairment centred gait analysis utilises kinematic deviations observed at the individual joint/plane level. The next part will present single joint/plane kinematic deviations observed in children with cerebral palsy and the impairments they may be associated with.

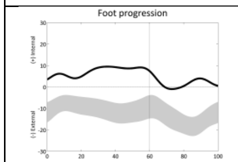
18.3. Kinematic Deviations in Children with Cerebral Palsy

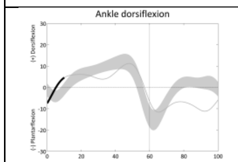
We present the major kinematic deviations from normal and the primary impairments linked to these deviations in the next table (Table 1). The table has seven columns, the 1st presents a graph of the deviation, the 2nd describes the joint, plane and (timing) it is observed, the 3rd presents the impairments (•) and lists associated deviations (○).

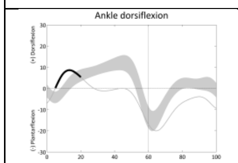
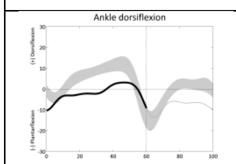
We recognise that some kinematic deviations may come secondary to another problem or as compensation for another deviation.

Table 1. Twenty-four frequent single joint/plane kinematic deviations

Graph	Description	Impairments and coherent gait data	Confounding factor
	External foot progression (stride)	• Increased external tibial torsion • Foot deformity ○ Increased ankle external rotation	• Sustained pelvic retraction • Increased hip external rotation

	Internal foot progression (stride)	• Increased femoral anteversion
		  ○ Increased hip internal rotation
		• Reduced external tibial torsion
		• Foot deformity
		  ○ Increased internal ankle rotation
			• Sustained pelvic protraction

	Absent ankle 1st rocker (1st double support)	• Ankle dorsiflexors weakness or reduced selective motor control
		  ○ Excessive plantarflexion (swing)
		• Plantarflexors contracture or overactivity
		  ○ Excessive plantarflexion (stride)
			• Leg length discrepancy

	Early ankle plantarflexion (early stance)	• Plantarflexors overactivity ○ Premature knee extension/hyperextension	• Leg length discrepancy or foot clearance problem on contralateral side • Increased knee flexion
	Lack of ankle dorsiflexion (stance)	• Plantarflexors contracture or overactivity	

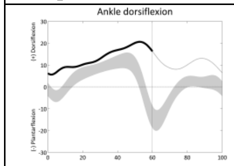
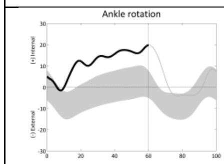
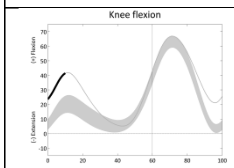
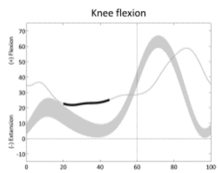
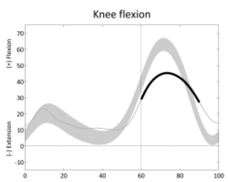
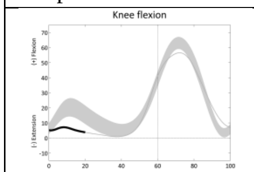
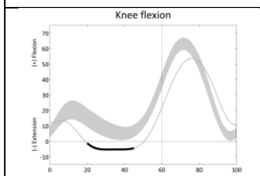
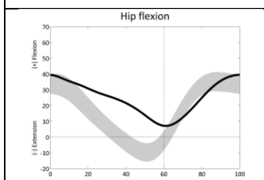
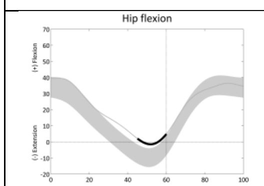
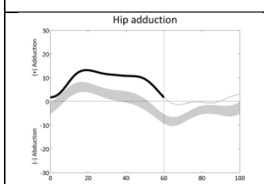
Graph	Description	Impairments and coherent gait data	Confounding factor
	Increased ankle dorsiflexion (stance)	• Soleus weakness or soleus too long ○ Increased knee flexion in mid-stance	
	Increased ankle internal rotation (stance)	• Foot deformity – Metatarsus adductus, cavo-varus ○ Internal foot progression • Tibialis posterior overactivity ○ Tibialis posterior EMG	
	Increased knee flexion (loading response)	• Hamstring overactivity • Plantarflexors contracture or overactivity ○ Excessive ankle plantarflexion	
	Reduced knee extension (mid-stance)	• Hamstring contracture or overactivity • Knee fixed flexion deformity • Hip extensors or knee extensors weakness ○ Excessive hip flexion • Ankle plantarflexors weakness ○ Excessive ankle dorsiflexion • Ankle plantarflexors overactivity or contracture ○ Excessive ankle plantarflexion	• Cross-plane interactions (transverse - sagittal) ○ External tibial torsion ○ Increased femoral neck anteversion ○ Foot deformity
	Reduced or delayed knee flexion (swing)	• Rectus femoris overactivity ○ Rectus femoris EMG activity in late stance or early swing • Stiff-knee gait, hamstring/rectus co-contraction	• Cross-plane interaction (transverse - sagittal) if retracted pelvis and hip externally rotated • Reduced push-off during ankle 3^{rd} rocker • Reduced speed

Table 1. (Continued)

Graph	Description	Impairments and coherent gait data	Confounding factor
	Reduced knee flexion (loading response)	• Quadriceps weakness or patella pain ○ Reduced knee extensor moment (stance)	
	Knee hyper extension (mid-stance)	• Quadriceps weakness • Plantarflexors overactivity or contracture ○ Excessive ankle plantarflexion	
	Increased hip flexion (stride)	• Hip flexor contracture or overactivity ○ Anterior pelvic tilt, double bump • Hip extensor weakness	• Sustained anterior pelvic tilt (stride) • Excessive knee flexion • Leg length discrepancy
	Lack of hip extension (2nd double support)	• Hip flexor contracture or overactivity ○ Anterior pelvic tilt, double bump • Hip reduced range of movement ○ Anterior pelvic tilt, single bump	• Leg length discrepancy
	Increased hip adduction (stance)	• Hip abductor weakness ○ Contralateral pelvic drop • Hip adductor contracture or overactivity	• Increased hip internal rotation • Pelvic retraction or obliquity • Leg length discrepancy

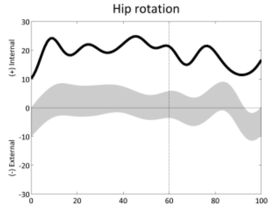
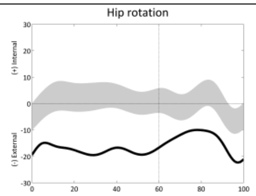
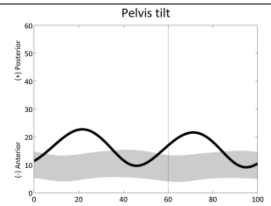
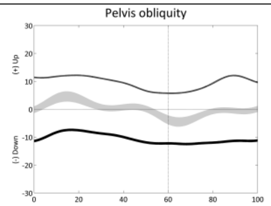
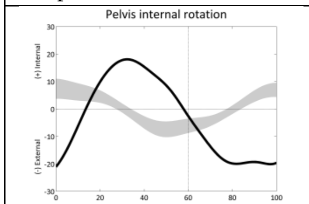
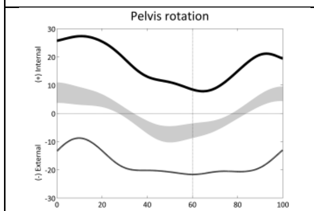
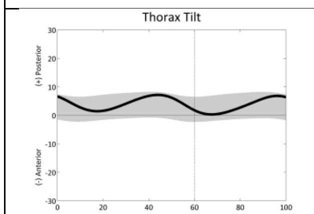
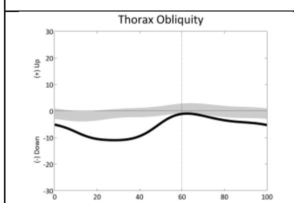
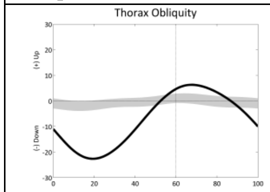
Graph	Description	Impairments and coherent gait data	Confounding factor
	Increased internal hip rotation (stride)	• Increased femoral neck anteversion • Excessive external tibial torsion	• Pelvic retraction on ipsilateral side
	Increased external hip rotation (stride)	• Reduced femoral anteversion • Reduced external tibial torsion	• Pelvic protraction on ipsilateral side • Obesity/large thighs • Foot deformity
	Pelvic tilt double bump (stride)	• Hip flexors contracture or overactivity ○ Reduced hip extension	
	Pelvic obliquity down or up (stride)	• Leg length discrepancy ○ Excessive hip abduction • Adductors contracture	• Scoliosis • Hemiplegia

Table 1. (Continued)

Graph	Description	Impairments and coherent gait data	Confounding factor
	Reversed pelvic rotation profile (stride)	• Overall weakness ○ Reversed hip adduction profile	
	Sustained pelvic pro or re-traction (stride)	• Asymmetry in overall weakness	• Femur torsional deformity • Tibia torsional deformity • Hemiplegia
	Trunk tilt, double bump (stride)	• Overall weakness	
	Sustained trunk obliquity (stride)	• Hip pain (unilateral) • Abductors weakness (unilateral)	

Graph	Description	Impairments and coherent gait data	Confounding factor
	Excessive range of trunk obliquity, Trendelenburg (stride)	• Abductors weakness	

These confounding factors (•) are listed in the last column. One confounding factor appears several time: leg length discrepancy.

Leg length discrepancy may be anatomical, when physical examination or medical imaging measures a true length difference between the legs, or functional, when the combination of joint angles during single leg support in stance results in altered leg length.

The deviations are ordered from distal to proximal joints/segments and in the sagittal, coronal and transverse planes. In each graph, the light grey band presents the pattern of 35 typically developed children (the width equates to one standard deviation). The solid curve presents an example of altered kinematics, the part of interest is emphasized by a bolder line for the time instants of interest. Two pelvic deviations show two lines (one solid, one dashed) for the two sides of the same patient.

CONCLUSION

This chapter tried to differentiate between the clinical gait patterns, which provide a common language and assist with broad management algorithms and individual kinematic deviations, which support clinical decision-making in gait analysis. The main clinical gait patterns for children with unilateral or bilateral spastic cerebral palsy were presented and 24 frequent single joint/ plane kinematic deviations were tabulated. This list is not exhaustive and the precise understanding of gait deviations in cerebral palsy is still the object of extensive research. Clinical gait analysis, which provides an objective measurement of gait, is an excellent tool to identify as best as possible gait deviations and possible linked impairments. This information is the basis for the planning of treatment.

ACKNOWLEDGMENTS

We would like to acknowledge Jessica Pascoe, senior physiotherapist at the Hugh Williamson Gait Analysis Laboratory at The Royal Children’s Hospital, Melbourne Australia, for her help with the kinematic deviations table.

REFERENCES

[1] Winters, T. F., Jr., J. R. Gage and R. Hicks, Gait patterns in spastic hemiplegia in children and young adults. *J. Bone Joint Surg. Am*., 1987. 69(3): p. 437-41.

[2] Stout, J., J. R. Gage and A. E. Van Heest, Hemiplegia: pathology and treatment, In: *Treatment of Gait Problems in Cerebral Palsy*, M.K. Press, Editor. 2004, Wiley: London. p. 320-1.

[3] Rodda, J. and H. K. Graham, Classification of gait patterns in spastic hemiplegia and spastic diplegia: a basis for a management algorithm. *European journal of neurology: the official journal of the European Federation of Neurological Societies*, 2001. 8 Suppl. 5: p. 98-108.

[4] Rodda, J. M., H. K. Graham, L. Carson, et al., Sagittal gait patterns in spastic diplegia. *The Journal of bone and joint surgery*. British volume, 2004. 86(2): p. 251-8.

[5] Rang, M., Cerebral Palsy, In: *Pediatric Orthopaedics*, W. W. Lovell and R. B. Winter, Editors. 1990, J.B. Lippincott: Philadelphia. p. 465-506.

[6] Sutherland, D. H. and J. R. Davids, Common gait abnormalities of the knee in cerebral palsy. *Clinical Orthopaedics*, 1993. 288(March): p. 139-147.

[7] Miller, F., K. W. Dabney and M. Rang, *Complications in cerebral palsy treatment*, in *Complications in Pediatric Orthopaedic Surgery*, C. H. Epps and J. R. Bowen, Editors. 1995, J.B. Lippincott Company: Philadelphia. p. 477-544.

[8] Dobson, F., M. E. Morris, R. Baker, et al., Gait classification in children with cerebral palsy: a systematic review. *Gait Posture*, 2007. 25(1): p. 140-52.

[9] O'Byrne, J. M., A. Jenkinson and T. M. O'Brien, Quantitative analysis and classification of gait patterns in cerebral palsy using a three-dimensional motion analyzer. *Journal of Child Neurology*, 1998. 13(3): p. 101-108.

[10] Rozumalski, A. and M. H. Schwartz, Crouch gait patterns defined using k-means cluster analysis are related to underlying clinical pathology. *Gait and posture*, 2009. 30 (2): p. 155-60.

[11] Bonnefoy-Mazure, A., Y. Sagawa, Jr., P. Lascombes, et al., Identification of gait patterns in individuals with cerebral palsy using multiple correspondence analysis. *Res. Dev. Disabil.*, 2013. 34(9): p. 2684-93.

[12] Sangeux, M., J. Rodda and H. K. Graham, Sagittal gait patterns in cerebral palsy: The plantarflexor-knee extension couple index. *Gait Posture*, 2015. 41(2): p. 586-91.