BEST PRACTICES MANUAL
FOR CLINICAL GAIT ANALYSIS WITH CHILDREN WITH CEREBRAL PALSY

FACULTY FOR HUMAN KINETICS - UNIVERSITY OF LISBON
Biomechanics and Functional Morphology Laboratory

2025

António Veloso, Filipa João, Filomena Carnide, Sílvia Cabral, Vera Moniz Pereira

Project
Development of a simulation platform based in musculoskeletal models to predict recovery of gait following orthopedic interventions in cerebral palsy children.

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CONTENTS

Acknowledgments....4

Introduction....5

1 Physical Examination....6

1.1 Anthropometric Measures....6

1.2 Goniometric, Force and Spasticity Measures....7

2 Gait data collection....20

2.1 2D Video Analysis....20

2.1.1 CLINICAL VIDEO CAPTURE PROTOCOL....21

2.1.2 GAIT OBSERVATION SCALES (CLINICAL VIDEO)....22

2.2 3D Instrumented Gait Analysis....23

2.2.1 Marker-based Motion Capture Systems....24

2.2.2 Markerless Motion Capture Systems....29

2.3 Electromyography....30

2.3.1 Skin Preparation....31

2.3.2 Electrodes Placement and data collection....31

3 Musculoskeletal Modelling....33

4. Questionnaires....34

Appendix....44

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Our sincere thanks go to the patients, participants and their families whose willingness to engage in gait assessments continually pushes the field forward. Their trust enables the refinement of methods, the validation of new technologies, and the advancement of interventions that improve mobility and quality of life. This book is ultimately dedicated to them, as their experiences remain at the heart of clinical gait analysis.

Finally, we are indebted to our colleagues, mentors, and collaborators who provided thoughtful feedback, constructive criticism, and unwavering support. Their perspectives enhanced the clarity, rigor, and relevance of this work.

Introduction

This Best Practice Manual is designed to support biomechanists and health professionals in the comprehensive preparation and execution of gait analysis in children and adults with cerebral palsy. Cerebral Palsy is the most common cause of motor disability in childhood. Treatment planning and monitoring of patients frequently rely on several aspects, such as a physical examination, data collection and electromyography, which are covered in this document. Gait analysis in this population requires a multidisciplinary and methodologically rigorous approach to ensure the data collected is clinically meaningful and relevant to treatment planning.

Altogether, this manual serves as a step-by-step guide to ensure a standardized, thorough, and clinically informed approach to gait analysis in children with cerebral palsy, optimizing the quality of data collected and its value in guiding intervention planning.

This manual comprises 3 areas of assessment:

a) the physical examination, where standardized measurements of selective motor control, muscle tone, bone and joint deformities and muscle length/contractures are performed;

b) the gait data collection, where all the procedures are detailed, from participant preparation to data treatment;

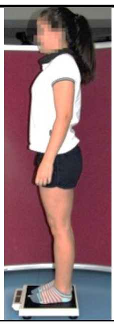
c) population specific questionnaires, where data about health, physical activity and quality of life are collected;

1 Physical Examination

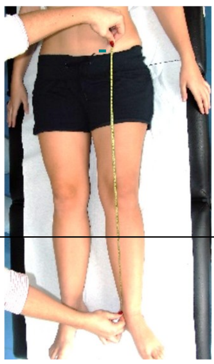
(Carolina Escalda, Filipa João, João Campagnolo, Patrícia Mota, Susana, Almeida, Vera Bagão,)

During a biomechanical session at the laboratory, there should be a clinical examination that consists of measuring anthropometric features such as height, mass and lower limb length; muscle strength using manual techniques and a modified Oxford scale (Appendix 2); bone torsions, joint deformities and muscle length using goniometry, and spasticity using Tardieu method and Ashworth scale (Appendix 1). Selective motor control can also be measured with the force tests. This physical examination should be performed by at least two persons, preferably a physiotherapist and/or a clinician with experience in physical examination.

1.1 Anthropometric Measures

1. Mass		
	**Materials**	Electronic weighing scale.
	Procedure	The subject is asked to step on the weighing device, looking forward. The examiner should provide minimum support as possible.
	Measure	Mass (kg).
	Remarks	Rounded to one decimal case.

2. Total Height		
	**Materials**	Stadiometer.
	Procedure	The subject is asked to step on the stadiometer's base, with the back facing the scale. Looking forward, and provided with the needed support, the subject should be encouraged to stand as straight as possible. The sliding headboard should then be lowered to the vertex of the head.
	Measure	Stature (m).
	Remarks	Rounded to two decimal cases.

3. True Leg Length		
	**Materials**	Anthropometric tape.
	Procedure	With the subject lying supine, the anterior superior iliac spine (ASIS) must be detected. The examiner should guarantee that the knee is fully extended. Measure the distance between the ASIS and the ipsilateral medial malleolus.
	Measure	The straight-line distance between the ASIS and the medial malleolus (cm).
	Remarks	If moderate to severe deformities in the Sagittal or Frontal plane are present (fixed adducts, knee or hip flexum) the segments should be measured individually by considering the

		following bony references: Femur length — From ASIS to medial condyle. Tibial length — From medial condyle to medial malleolus. When applied, select the modified method on the assessment sheet.
4. Apparent Leg Length		
	**Materials:**	Anthropometric tape.
	Position:	Lying supine.
	Procedure:	The examiner should guarantee that the knee is fully extended. Measure the distance between the umbilicus and the ipsilateral medial malleolus.
	Measure:	The straight-line distance between the umbilicus and the medial malleolus (cm).
	Remarks:	If moderate to severe deformities in the Sagittal or Frontal plane are present (fixed adducts, knee or hip flexum) the segments should be measured individually by considering the following bony references: Femur length — From umbilicus to medial condyle. Tibial length — From medial condyle to medial malleolus. When applied, select the modified method on the assessment sheet.

1.2 Goniometric, Force and Spasticity Measures

5. Hip Flexion		
	**Structures**	All passive joint structures.
	Position	Supine lying. Both legs full extended.
	Stabilization	Stabilize contralateral thigh to maintain leg position.
	Procedure	Flex both hip and knee on the same side.
	Stable arm	Aligned with midline trunk side (from greater trochanter to glenohumeral joint).
	Mobile arm	Aligned with midline thigh.
	Measure	The angle between the trunk and the thigh segments (deg).
	Remarks	Assess only in children with very limited hip flexion.

6. Hamstrings Length Modified Popliteal Angle Bilateral		
	Structures	Hamstrings muscles.
	Position	Supine lying. Flex both hips until ASIS lies vertically over PSIS. The ipsilateral thigh is moved to be vertical.
	Stabilization	Stabilize contralateral thigh to maintain pelvis in the reference position.
	Procedure	Extend the knee from the assessed limb with

		sustained stretch until the pelvis starts to move or the child tries to extend the hip.
	Goniometer stable arm	Aligned with midline thigh (from lateral femoral condyle to greater trochanter).
	Goniometer mobile arm	Aligned with long axis of the tibia, from fibula head to the midpoint of ankle joint (sagittal plane).
	Measure	Angle from anatomical position (deg). Flexion is positive.
	Remarks	The long axis of the tibia is used because when marked tibial torsion is present, the posterior location of the lateral malleolus can be misleading.

7. Hamstrings Length Conventional Popliteal Angle Unilateral		
	**Structures**	Hamstrings muscles.
	Position	Supine lying. Flex the hip of the assessed limb until the thigh is vertical with the knee flexed.
	Stabilization	Stabilize contralateral thigh to maintain leg position.
	Procedure	Extend the knee from the assessed limb with sustained stretch until the pelvis starts to move or the child tries to extend the hip.
	Goniometer stable arm	Aligned with midline thigh (from lateral femoral condyle to greater trochanter).
	Goniometer mobile arm	Aligned with long axis of the tibia, from fibula head to the midpoint of ankle joint (sagittal plane).
	Measure	Angle from anatomical position (deg). Flexion is positive.
	Remarks	The long axis of the tibia is used because when marked tibial torsion is present, the posterior location of the lateral malleolus can be misleading.

8. Hamstrings Spasticity		
	**Structures**	Hamstrings muscles.
	Position	Supine lying. Flex the hip of the assessed limb until the thigh is vertical with the knee flexed. The contralateral limb rests on the table.
	Stabilization	Stabilize contralateral limb to maintain position and the assessed thigh to maintain vertical position.
	Procedure	1st: Extend the knee slowly until a catch is felt. Repeat this 3 times and register the angle on the 3rd time. 2nd: Repeat the 1st protocol but with a rapid knee extension and register the angle of catch (deg).
	Goniometer stable arm	Aligned with midline thigh (from lateral femoral condyle to greater trochanter).

	Goniometer mobile arm	Aligned with long axis of the tibia, from fibula head to the midpoint of ankle joint (sagittal plane).
	Measure	Tone: modified Ashworth scale (Appendix 1). Spasticity: modified Tardieu test (Tardieu, 1954) Flexion is positive.
	Remarks	The long axis of the tibia is used because when marked tibial torsion is present, the posterior location of the lateral malleolus can be misleading.

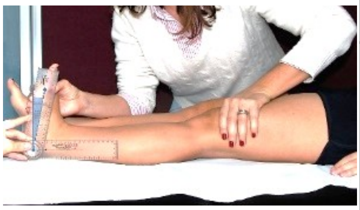
9. Knee Extension		
	**Structures**	Knee joint capsule and deformity of the distal femur or proximal tibia.
	Position	Supine lying.
	Procedure	Knee is extended to the end of range; gentle pressure should be applied on the distal femur.
	Goniometer stable arm	Aligned with midline thigh (from lateral femoral condyle to greater trochanter).
	Goniometer mobile arm	Aligned with long axis of the tibia, from fibula head to the midpoint of ankle joint (sagittal plane).
	Measure	Angle from anatomical position (deg). Hyperextension is positive.
	Remarks	The long axis of the tibia is used because when marked tibial torsion is present, the posterior location of the lateral malleolus can be misleading.

10. Soleus Length - Silfverskiöld Test		
	**Structures**	Soleus muscle.
	Position:	Supine lying. The hip and knee are flexed to 90 deg and the ankle is relaxed.
	Stabilization	To maintain the hip and knee flexed at 90 deg. The midfoot should be held in sufficient inversion to prevent collapse of subtalar joint.
	Procedure	Manually dorsiflex the ankle until maximal stretch is held for a few seconds.
	Goniometer stable arm	Long axis of the tibia (from fibular head to midpoint of the ankle joint in sagittal plane).
	Goniometer mobile arm	Border of the lateral and plantarflexor surfaces of the foot.
	Measure	Angle from anatomical position (deg). Dorsiflexion is positive.
	Remarks	If there is a significant mid-foot deformity, the border of the hindfoot should be used for the mobile arm of the goniometer.

11. Gastrocnemius Length – Silfverskiöld Test

Structures	Gastrocnemius muscle.
Position	Supine lying. Start with the lower limbs in the same position of the endpoint of the soleus length test (ankle in maximal dorsiflexion).
Procedure	Extend the hip and knee while a maximal stretch is applied to the plantarflexors and maintained for a few seconds in the extended position. The foot is held in sufficient inversion to lock the subtalar joint.
Goniometer stable arm	Long axis of the tibia (from fibular head to midpoint of the ankle joint in sagittal plane).
Goniometer mobile arm	Border of the lateral and plantarflexor surfaces of the foot.
Measure	Angle from anatomical position (deg). Dorsiflexion is positive.
Remarks	If there is a significant mid-foot deformity, the border of the hindfoot should be used for the mobile arm of the goniometer.

12. Gastrocnemius Spasticity and Tone



Structures	Gastrocnemius muscle.
Position	Supine lying with the hip and knee extended.
Procedure	1st: plantarflex the ankle slowly (keep the subtalar joint as neutral as possible) until a catch is felt. Repeat this 3 times and register the modified Asworth score – Appendix 2. 2nd: Repeat the 1st protocol but with a rapid ankle plantarflexion and at the 3rd time register the angle of catch.
Goniometer stable arm:	Long axis of the tibia (from fibular head to midpoint of the ankle joint in sagittal plane).
Goniometer mobile arm:	Border of the lateral and plantarflexor surfaces of the foot.
Measure:	Spasticity: modified Tardieu test – (Tardieu, 1954) Dorsiflexion is positive. Tone: modified Asworth scale – Appendix 2
Remarks	If there is a significant midfoot deformity, the border of the hindfoot should be used for the mobile arm of the goniometer. Measure both in crouch gait children. If not, **measure only spasticity**.

13. Hip Adductor Length

	**Structures**	Hip adductors and medial hamstrings muscles, medial hip joint capsule in the absence of muscle contractures.
	Position	Supine lying with the hip and knee extended (neutral).
	Stabilization	Maintain pelvis neutral or counter-movement opposite extremity to provide resistance to stretch.
	Procedure	Move assessed limb into abduction applying a stretch for a few seconds.
	Goniometer stable arm	From one ASIS to the other.
	Goniometer mobile arm	From ASIS parallel to the mid-line of the thigh.
	Measure	Angle from anatomical position. Hip abduction is positive.
	Remarks	When hip abduction with knees extended is less than 20 deg, assess "Hip adductor length with hips extended and knees flexed" **or** "Hip adductor length with hips flexed and knees flexed" according with the patient condition.

14. Hip Adductor Length with Hips Extended and Knees Flexed		
	**Structures**	Hip adductors muscles (without gracilis); medial hip joint capsule in the absence of muscle contractures.
	Position	Supine lying with the hips extended and the knees flexed 90 deg over the end of the table.
	Stabilization	Held the contralateral lower limb and maintain the pelvis neutral in transverse plane and hips neutral in sagittal and transverse planes.
	Procedure	Move assessed limb into abduction applying a stretch for a few seconds.
	Goniometer stable arm	From one ASIS to the other.
	Goniometer mobile arm	From ASIS parallel to the mid-line of the thigh.
	Measure	Angle from anatomical position. Hip abduction is positive.

15. Hip Adductor Length with Hips Flexed and Knees Flexed		
	Structures	Hip adductors; medial hip joint capsule in the absence of muscle contractures.
	Position	Supine lying with the hips and the knees flexed to 90 deg.
	Stabilization	Held the contralateral lower limb and maintain the pelvis and hips neutral in transverse plane.

	**Procedure**	Move both limbs into abduction together applying a stretch for a few seconds.
	Goniometer stable arm	Along the examination table (use a large semicircular goniometer) with the goniometer centre placed in line with the ischial tuberosity.
	Goniometer mobile arm	Parallel to the mid-line of the thigh (from hip joint to knee joint).
	Measure	Angle from the vertical. Abduction is positive.

16. Knee Extension (Quadriceps Lag)		
 	**Structures**	Vasti muscles and rectus femoris muscle.
	Position	Sitting over the edge of the table, feet unsupported, hips neutral, tibia vertical and leaning back on hands if necessary to release stretching on hamstrings.
	Stabilization	Stabilize the thigh at 1/3 distally.
	Procedure	Place one hand under the distal third of the posterior tibia and passively extend the knee to the full available range. Then ask the patient to maintain this degree of extension while slowly and gradually reduce the support of the leg. If the tibia drops when support is removed, this degree of flexion is measured.
	Goniometer stable arm	Aligned with long axis of the femur (from lateral femoral condyle to greater trochanter).
	Goniometer mobile arm	Aligned with long axis of the tibia, from fibula head to the midpoint of ankle joint (sagittal plane).
	Measure	The difference between the angle measured passively (full knee extension) and the angle of knee extension that the patient can maintain by himself.

17. Hip Flexor Length – modified Thomas Test		
	**Structures**	Psoas muscle (anterior capsule in absence of muscle contracture).
	Position	Supine lying anatomical position with buttocks close to edge of the table so that hip extension is not restricted. Start with both hips and knees flexed until the ASIS are vertically above the PSIS.
	Stabilization	Hold the contralateral thigh in the previous position.
	Procedure	Passively allow the assessed limb to extend till its maximum by the weight of the limb and add a gentle stretch by the examiner. The knee is allowed to flex as is comfortable.

	Goniometer stable arm	Aligned with horizontal.
	Goniometer mobile arm	Aligned with long axis of the femur (from greater trochanter to lateral femoral condyle).
	Measure	The angle from the anatomical position. Hip hyperextension is positive.

18. Hip Flexor Strength

	**Structures**	Hip flexor globally (psoas, rectus anterior).
	Position	Sitting upright, with the knees bent over the side of the table.
	Stabilization	The weight of the trunk may be sufficient to stabilize the patient during the test but holding on to the table gives added stability. If the trunk is weak, the supine position may be assumed.
	Procedure	Hip flexion with the knee flexed, raising the thigh from the table.
	Resistance	Against the anterior thigh, in the direction of extension.
	Remarks	Measure with modified oxford scale – Appendix 2.

19. Knee Extensors Strength

	**Structures**	Vasti muscles and rectus femoris muscle.
	Position	Sitting over the edge of the table, feet unsupported, hips neutral, tibia vertical and leaning back on hands if necessary to release stretching on hamstrings.
	Stabilization	Stabilize the thigh at 1/3 distally.
	Procedure	Knee extension.
	Resistance	Against the distal portion of the anterior shank, in the direction of extension.
	Remarks	Measure with modified oxford scale – Appendix 2.

20. Rectus Femoris Length

	**Structures**	Rectus femoris muscle.
	Position	Prone lying with hips and knees extended.
	Procedure	Flex the knee with the hip extended, pressing the buttocks to keep the hip extended and keep the stretch for a few seconds.
	Goniometer stable arm	Aligned with long axis of the femur (from greater trochanter to lateral femoral condyle).
	Goniometer mobile arm	Long axis of the tibia (from fibular head to midpoint of the ankle joint in sagittal plane).
	Measure	Angle from anatomical position. Flexion is positive.

21. Rectus Femoris Spasticity – Duncan-Ely Test		
	**Structures**	Rectus femoris muscle.
	Position	Prone lying with hips extended.
	Procedure:	1- The knee is flexed, passing slowly from an extended position to a flexed one, to assess tone. Repeat 3 times. 2- The knee is flexed rapidly over 3 consecutive trials to assess spasticity.
	Measure	Positive or Negative for each condition. The test is considered positive if the patient simultaneously flexes the ipsilateral hip or resistance is felt by the examiner.

22. Hip Internal Rotation Range		
	**Structures**	Hip capsule, ligaments and external rotation.
	Position	Prone lying. Hips extended and knees flexed to 90 deg.
	Stabilization	The pelvis and hips are stabilised in neutral position in the transverse plane.
	Procedure	Both hips are internally rotated until reasonable stretch.
	**Goniometer stable arm**	Along the examination table (use a large semicircular goniometer).
	Goniometer mobile arm	Long axis of the tibia, taken as the line between the midpoint of the femoral epicondyles and the midpoint of the malleoli.
	Measure	Angle between the vertical and the shank. Internal rotation is positive.
	Remarks	Ligaments laxity affecting measurements should be noted.

23. Hip External Rotation Range		
	**Structures**	The ligaments of hip joint capsule.
	Position	Prone lying. Hip extended and knee flexed to 90 deg.
	Stabilization	The pelvis is held by the assistant to be neutral in the transverse plane.
	Procedure	The knee is flexed 90 deg. It is then externally rotated until the pelvis starts to move despite stabilization.
	Goniometer stable arm	Along the examination table (use a large semicircular goniometer).
	Goniometer mobile arm	Long axis of the tibia, taken as the line between the midpoint of the femoral epicondyles and the

		midpoint of the malleoli.
	Measure	Angle between the vertical and the shank. External rotation is positive.
	Remarks	Ligaments laxity affecting measurements should be noted.

24. Trochanteric Prominence Angle Test (Femoral Anteversion)

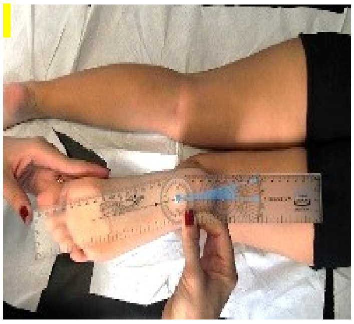
Structures	The alignment of the femoral neck to the transcondylar axis.
Position	Prone lying. Hips and knees extended.
Stabilization	The pelvis is stabilised by the examiner to prevent rotation in transverse plane.
Procedure	The examiner stands on one side of the patient to palpate the greater trochanter on the other side. The knee is flexed to 90 deg and the examiner palpates the great trochanter. The hip is rotated and stopped when the great trochanter is more prominent.
Goniometer stable arm	Along the examination table (use a large semicircular goniometer).
Goniometer mobile arm	Long axis of the tibia, taken as the line between the mid-point of the femoral epicondyles and the midpoint of the malleoli.
Measure	Angle between the vertical and the shank. Internal rotation is positive, indicating anteversion.

25. Tibial Torsion (bimalleolar axis)

Structures:	The torsional alignment of the tibia
Position	Prone lying. Knees flexed to 90 deg and ankles in neutral position.
Stabilization	Stabilize the hindfoot.
Procedure	The examiner gets above the table and the patient to look down on the plantar surface of the foot.
Goniometer stable arm	Placed on the heel pad and aligned perpendicularly to the long axis of the femur.
Goniometer mobile arm	Placed on the heel pad and aligned with the bimalleolar axis of the foot.
Measure:	Angle between the knee joint axis (assumed to be perpendicular to the long axis of the femur) and the bimalleolar axis. External rotation of the distal segment is positive.
Remarks	used in children with foot deformities

26. Tibial torsion (thigh-hindfoot angle)

Structures	The torsional alignment of the tibia
Position	Prone lying. Knees flexed to 90 deg and ankles in



	neutral position.
Stabilization	Stabilize the hindfoot.
Procedure	The examiner gets above the table and the patient to look down on the plantar surface of the foot.
Goniometer stable arm	Align with the long axis of the femur.
Goniometer mobile arm	Along the midline of the hindfoot.
Measure	Angle between the long axis of the femur and the bisector of the heel pad. External rotation of the distal segment is positive.

27. Hindfoot-Forefoot Angle

Structures	The alignment of the hindfoot with the forefoot
Position	Prone lying. Knees flexed to 90 deg and ankles in neutral position.
Stabilization	Stabilize the hindfoot.
Procedure	The examiner gets above the table and the patient to look down on the plantar surface of the foot.
Goniometer stable arm	Along the midline of the hindfoot.
Goniometer mobile arm	Along the midline of the forefoot, toward the 2nd toe.
Measure	Angle between the bisector of the heel pad, and the long axis of the forefoot (assumed to lie on the second ray). External rotation of the distal segment is positive.

28. Hip Extensor Strength

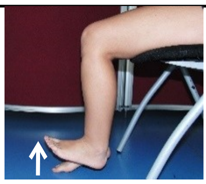
Structures	Gluteus maximus muscle.
Position	Prone, with the knee flexed at 90 deg.
Stabilization	Posteriorly, on the back muscles.
Procedure	Hip extension with knee flexed.
Resistance	Against the lower part of the posterior thigh in the direction of hip flexion.
Remarks	If hip flexum is present the modified test can be performed. Same procedure, but the patient is in prone with the legs hanging over the end of the table.

29. Knee Flexor Strength

Structures:	Hamstrings muscles.
Position	Prone.
Stabilization	Hold the thigh firmly down on the table.

	**Procedure**	Ask for knee flexion until 90 deg.
	Resistance	With the knee flexed between 50-70 deg resist against the leg, proximal to the ankle, in the direction of knee extension. Do not apply pressure against the rotation component.
	Remarks	To assess the biceps femoris or semitendinosus strength separately, perform an internal or external rotation, respectively, with the knee flexion.

30. Abductor Strength		
	**Structures:**	Gluteus minimus and medius muscles.
	Position:	Side-lying, with the underneath leg flexed at the hip and knee and the pelvis rotated slightly forward.
	Stabilization	The muscles of the trunk and the examiner stabilize the pelvis.
	Procedure	Abduction of the hip with slight extension and slight external rotation. The knee is maintained in extension.
	Resistance	Against the leg, near the ankle, in the direction of adduction and slight flexion; *do not* apply pressure against the rotation component. The pressure is applied against the leg for the purpose of obtaining a long lever.
	Remarks	Differentiating the posterior gluteus medius is very important. Hip abductors, when tested as a group, may be normal in strength, even though a precise test of the gluteus medius may reveal appreciable weakness.

31. Selective motor control tests – seated on a chair		
	**Procedure and measure**	Ask the patient to dorsiflex the ankle against gravity. Use Boyd & Graham scale – Appendix 3. for selective motor control.
	**Procedure and measure**	Ask the patient to invert the ankle.

	**Procedure and measure**	Ask the patient to evert the ankle.
	**Procedure and measure**	Ask the patient to flex the hip (bring the knee up) against gravity. Observe the foot to see if the ankle dorsiflexes at the same time. Positive (+) if active dorsiflexion occurs when the patient is asked to flex the hip. Patients with little voluntary control of dorsiflexion are sometimes able to illicit active dorsiflexion in this way. It can be useful to note whether pure dorsiflexion occurs or whether this is accompanied by inversion or eversion of the foot. May represent neurological maturation and be positive in some children with normal development.

32. Ankle plantarflexor strength (Standing)		
 	**Structures**	Gastrocnemius and soleus muscles.
	Position	Weight-bearing in a normal standing position.
	Stabilization	Holding the top of the table or a chair.
	Procedure	Ask for 10 reps of calf raise.
	Remarks	If the test is weak, perform it with in a seated position.

33. Feet Posture and other deformities (standing position)		
	Dorsal Bunion (hallux rigidus)	Check if there is dorsiflexion of the first toe. Register Yes or No.
	Hallux Valgus	Check if there is lateral deformation of the first toe. Register Yes or No.
	Knee varus/valgus	Deformity of distal femur or proximal tibia. Hold the patient arms/hands if balance is needed. Observe the knee and look for any deformity.
	Ankle equinus/ calcaneous	Observe the ankle and register any deformity. Rate as Mild, Moderate or Severe deformity, if observed.
	Hindfoot valgus/ varus	Observe the hindfoot and register any deformity. Rate as Mild, Moderate or Severe deformity, if observed.
	Midfoot planus/ cavus	Observe the midfoot and register any deformity. Rate as Mild, Moderate or Severe

		deformity, if observed.
	Forefoot abduction/ adduction	Observe the forefoot and register any deformity. Rate as Mild, Moderate or Severe deformity, if observed.

2 Gait data collection

(Filipa João, Sílvia Cabral, Vera Moniz Pereira)

Gait analysis is an instrumented procedure that allows us to measure how much the participant's gait deviates from the normal pattern. It can be performed in two ways: with video analysis, being in this case an observational method, or a 3D instrumented gait analysis, where it is possible to quantify the main gait deviations in terms of kinematics, kinetics and muscle activation timing. Depending on the degree of CP severity, the availability of an instrumented biomechanics laboratory and the indication for surgical intervention, we may choose one of these two possibilities. The following sub-chapters will briefly detail both analyses.

2.1 2D Video Analysis

A 2D video analysis is recommended when an instrumented biomechanics laboratory is not available, or if the child has severe cognitive impairments that interfere with their ability to follow orders, for instance. In cases where the gait deviations are mild or during the first year of a rehabilitation process after surgery, a video analysis is also recommended.

BASIC PRINCIPLES OF VIDEO CAPTURE

Lighting: Proper lighting in the capture space is essential.

- Natural light or ceiling lighting is preferable to projectors (which may cause discomfort to the patient).
- Fluorescent lights can interfere with the image when using high sampling frequencies.
- Halogen lamps are a good option.
- Characteristics of video cameras affect the light reaching the sensor: lens size, aperture, capture frequency, or shutter speed.
- Increasing the aperture and gain can compensate for low lighting but may also introduce noise into the image.
- The recommended frame rate for gait analysis in a clinical setting is 25 to 50 frames per second, but shutter speeds of 1/125 or 1/250 seconds may be necessary to improve video quality.

Space dimensions – Field of view: Whenever possible, the optimal field of view should be used by adjusting the camera's zoom (optical zoom should be preferred over digital zoom, as the latter reduces image resolution). In normal walking, a person's step length is approximately 80% of their height. The conventional video aspect ratio is 3:4 (about 1.7 steps when adjusting the video height to the subject's height in the sagittal plane). Ideally, a 9:16 format should be used, as it allows capturing at least one full step from each side. At the beginning of the session, the patient should be photographed standing, and the zoom should be adjusted according to their height.

Capture Planes:

In a clinical setting, the ideal approach is to capture a pure sagittal plane and a pure frontal plane by positioning the camera perpendicular to each of these planes. However, only in the central region (approximately 1.5 m—corresponding to one adult step) are these planes truly sagittal or frontal. In other areas of the image, the patient will appear to be walking at an angle relative to the camera (parallax effect**)**. This effect increases as the patient moves away from the central field of view but can be reduced by placing the camera farther from the patient.

A balance must be found between image lighting and camera distance to reduce parallax. The ideal approach is to first ensure the best possible lighting and then gradually move the camera back while using zoom to match the patient's height. In most cases, the camera's positioning and distance depend on the available space, which may not always be large enough.

The camera should remain fixed, so using a tripod is recommended, as it allows for easy adjustments. Different walking conditions should be captured: barefoot, with orthoses when applicable and using walkers, crutches, or other mobility aids.

2.1.1 CLINICAL VIDEO CAPTURE PROTOCOL

There should be a standardized video capture protocol, to which additional information should be added whenever necessary. The standard procedure should always include gait collection in the sagittal and frontal planes of the patient, either barefoot and/or using orthoses, specific footwear, or other assistive walking devices. If there are limitations (such as equipment or time constraints), the examiner must ensure that the recorded data is representative of the patient's general gait pattern. An example of a standard protocol with fixed cameras in the sagittal and frontal planes is the one described by Baker (2013), in which sequences of gait cycles, changes in direction, and gait initiation are recorded (Fig. 3 and Table 2).

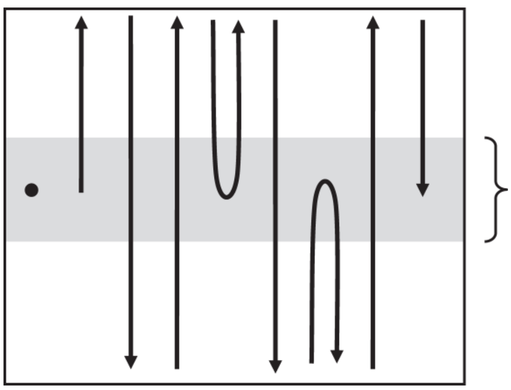


Fig.3: Gait Sequence. Adapted from Baker (2013)

Tabela 2 – Gait Sequence. Adapted from Baker (2013)

1	Position the patient in the center of the camera's field of view, adjusting the zoom according to their height.
2	Begin walking towards one end of the corridor.
3	Turn around and walk in the opposite direction toward the other end of the corridor.
4	Turn around and walk in the opposite direction toward the other end of the corridor.
5	Turn around, walk to the middle of the corridor, turn again, and walk to the end from which they originally came.
6	Turn around and walk in the opposite direction toward the other end of the corridor.
7	Turn around, walk to the middle of the corridor, turn again, and walk to the end from which they originally came.
8	Turn around and walk in the opposite direction toward the other end of the corridor.
9	Turn around and walk to the middle of the corridor, where the patient stops.

2.1.2 GAIT OBSERVATION SCALES (CLINICAL VIDEO)

Observing and evaluating gait videos with the eye presents challenges in terms of objectivity, consistency, and reliability. To mitigate these issues, several scales and assessment forms have been developed (Viehweger et al., 2010), primarily evaluating kinematic gait parameters. Rathinam and colleagues (2014) review article examined various tools for pediatric gait assessment through observation (Rathinam, Bateman, Peirson, & Skinner, 2014). This review included studies involving children up to 18 years old with neurological, neuromuscular, orthopedic conditions, or other developmental delays due to genetic disorders. Only studies assessing reliability and validity using instrumented gait analysis in children with cerebral palsy (CP) were included, resulting in a total of 9 studies. Among these, 5 developed and standardized their own original scales, while the remaining 4 were modifications of these scales.

Gait Observation Scales in the Sagittal, frontal and transverse planes

a. **Observational Gait Analysis** (OGA) (Mackey, Lobb, Walt, & Stott, 2003) and **Visual Gait score** (Kawamura et al., 2007)

— Ordinal scale assessing hip, knee, ankle, and pelvis (10 items) in the sagittal, frontal, and transverse planes.

— Evaluates whether joint positioning is normal, increased, or reduced.
— Showed high inter-observer agreement for knee flexion at initial contact and pelvic obliquity when compared to instrumented gait analysis. However, agreement was low for the remaining 8 parameters.

b. **Observational Gait Scale** (Araujo, Kirkwood, & Figueiredo, 2009)

  — Nominal scale assessing 24 key gait kinematics parameters, distributed as follows: Ankle/foot: 6 items; Knee: 5 items; Hip: 8 items; Pelvis**:** 5 items
  — Developed with consideration of examiner experience and training levels.
  — Does not specify scoring details.

c. **Edinburgh Visual Gait Score** (EVGS) (Read, 2003; Ong et al., 2008; Viehweger et al., 2010)

  — Numerical scale evaluating 17 parameters across ankle, knee, hip, pelvis, and trunk in the sagittal, frontal, and transverse planes.
  — Focuses on critical gait aspects in children with CP.
  — Uses a 3-point scale to indicate deviation severity from normal gait: (0 = Normal; 1 = Moderate deviation; 2 = Severe deviation).
  — Total score ranges from 0 to 34.
  — Demonstrated high intra- and inter-observer reliability, even among less experienced assessors.
  — Shows strong correlation with instrumented gait analysis, making it a validated tool.
  — Proven effective in detecting post-multilevel surgery gait changes (Viehweger et al., 2010).

Based on the review of the main observational gait scales in children with CP, we decided to use the Edinburgh Visual Gait Score (Read, 2003)

2.2 3D Instrumented Gait Analysis

A 3D instrumented gait analysis is recommended in the cases of children with gait deviations that suggest an increased possibility of surgical intervention. Moreover, kinetic and/or electromyography data are easier to collect in an instrumented facility, being therefore the best recommendation and the reference method for gait analysis. Here’s an example of an experimental protocol for gait analysis in our laboratory:

<u>Static Trial</u>: The subject stands static, oriented on the positive YY direction of the LAB for a few seconds, without assistance, in a neutral anatomical position (as much as possible) and positioning each foot in a force plate.

<u>Dynamic Trials</u>: the subject walks along the smaller/larger axis of the force plates, depending on the step length. Capture dynamic files of 30sec each and check the right and left cycles with good force plate data (at least 10 successful cycles for each side). Check the force plate's signal and EMG recording after the first trial.

Basic measurements

Spatiotemporal parameters	Length	**Step length** – Distance between consecutive heel strikes of opposite feet. **Stride length** – Distance between two consecutive heel strikes of the same foot.
	Duration	**Step time** – Time taken to complete a step. **Stride time** – Time taken to complete a stride.
	Cadence	Steps or strides per minute.
	Speed (m/s)	Distance per unit of time.
Kinematic parameters	Joint angle (º)	The rotation of the distal segment in relation to the proximal segment
Kinetic parameters	Joint moment (Nm/Kg)	Rotational force (torque) acting around a joint
	Joint power (W/Kg)	Rate of energy generation and absorption at joints
	Ground Reaction Forces (F)	Forces exerted by the ground on the body during walking or running

When using 3D Motion Capture (MOCAP) systems, the decisions lie on which marker setup to use, or opting for a markerless approach, which model to use (i.e. how the segments are defined and interconnected) and how to calculate the variables of interest (including sign convention).

2.2.1 Marker-based Motion Capture Systems

Marker-based systems are currently the reference for instrumented clinical gait analysis, and they have been used for decades. This technique requires the use of markers and cameras that capture infra-red light, allowing 3D motion tracking and further analysis using rigid bodies modelling software. Qualisys Track Manager (QTM) and Vicon have been the most common systems used for data acquisition. These systems rely on the accurate placement of reflective markers on specific anatomical landmarks of the subject's body to track movement. The marker setup will determine the position and orientation of the biomechanical model, so it is mandatory to firstly decide what biomechanical variables we want to calculate, in order to choose the best marker setup.

A biomechanical model is a collection of rigid bodies that represent skeletal structures, which we call segments. Each segment is entirely defined by a right handed orthogonal coordinate system and inertial properties (mass, center of mass location and principal moments of inertia). The construction of the segment's coordinate system requires at least 3 non-collinear markers. These markers, used to define the segment's coordinate system, must be placed in specific anatomical landmarks in order to create a coordinate system that makes intuitive sense and has anatomical meaning (i.e. the axes of the coordinate system should represent or be aligned with, as much as possible, the anatomical/functional axes of the segment).Furthermore the position and orientation of the segment's coordinate system should be defined using anatomical landmarks that are relatively easy to identify by palpation and of repeatable determination.

Marker Placement

There are various marker sets, which should be chosen depending on the type of movement to study and the degrees of freedom (dof) that we want our model to have. Some use a minimal number of markers for basic movement tracking, while others use additional markers to allow the study of more detailed biomechanical data with improved accuracy. In our laboratory, we use CAST marker setup (Cappozzo, 1995), which allows us to have 6 dof on every segment. Other advantages of CAST are: **a)** redundancy (has more markers than needed, which is useful in case of occlusion); **b)** clusters (facilitates marker placement process and minimizes skin movement artifacts) and **c)** anatomical markers (placed on subjects' body during the static trial and can be removed during dynamic trials). The positioning of the markers over the anatomical places requires previous training on anatomical palpation.

CAST marker set (adapted from Cappozzo, 1995)

Right	Left	Description and location
LAC	RAC	Follow the scapula's spine towards the shoulder joint, until you find the acromial angle. Follow the clavicle until you find the acromio-clavicular joint line (small depression). The marker should be placed on the midpoint of this line, which is obliquely oriented (shoulder top).
C7		C7 is the most prominent vertebra in the cervical region (when you see two prominences, C7 is« the one that does not disappear with head flexion).
STRN1 – 2		Placed on top of the sternum, one on the manubrium (midpoint), and the other on the midline of sternum's body (for tracking only).
RASIS	LASIS	Palpate along iliac crest in the anterior direction until you find the anterior superior iliac spine (flat surface after the end of the crest).
RPSIS	LPSIS	Palpate along iliac crest in the posterior direction until you find the posterior superior iliac spine (prominence at the posterior end of the crest).
RTH 1-4	LTH 1-4	Thigh cluster placed according with wobbling mass, visibility and sensors.

RLK	LLK	Placed on the lateral epicondyle of the knee - find the mid distance of the ROM, as the epicondyle will change position during the motion.
RMK	LMK	Placed on the medial epicondyle of the knee - find the mid distance of the ROM, as the epicondyle will change position during the motion.
RSK 1-4	LSK 1-4	Shank cluster placed according with wobbling mass, visibility and sensors.
RLA	LLA	Placed on the lateral malleolus along an imaginary line that passes through the transmalleolar axis.
RMA	LMA	Placed on the medial malleolus along an imaginary line that passes through the transmalleolar axis.
RHEE	LHEE	Place the HEE marker on the vertical posterior midline of the calcaneus, as far down the calcaneus as possible, considering heel strike during motion. It should have the same height from the plantar surface of the foot as the **P5M** marker.
RPCA	LPCA	Place the PCA marker on the same midline, above the **HEE** marker. (It will be used to define the calcaneus).
RP1M RP5M	LP1M LP5M	Place the P5M marker on the base of the 5th metatarsal. At the same height from the plantar surface of the foot as the markers on the metatarsal heads. Place the P1M marker on the base of the 1st metatarsal. Place markers immediately after the tarsometatarsal joints . The line connecting the mid-point of the markers on the base of the 1st and 5th metatarsals and the TOE marker represents the Ab/Adduction alignment of the forefoot.
RD1M RD5M	LD1M LD5M	Place the D1M marker on the head of the 1st metatarsal, and the D5M marker on the head of the 5th. Place markers immediately after the metatarsophalangeal joints, ensuring they are at the same distance from the plantar surface of the foot.
RTOE	LTOE	Place marker on the metatarsal area, between the 2nd and 3rd.
RHLX	LHLX	Place the HLX marker on the hallux on the proximal end of 1st distal phalange at the same height as the **D1M** marker.

Foot models

Whenever the focus of gait analysis is the foot segment, it should be modeled not just as a single segment but divided into two or three compartments. This allows us to analyze the foot segment by looking separately at the rearfoot, midfoot and toes. There are several foot models developed, accordingly with the purpose of the gait analysis. The Oxford Foot Model (Carson, 2001) is one example of a clinically validated marker set which represents the foot as multi-segment model, allowing for a detailed analysis of the mechanics of the foot during walking. It is based on two main foot segments, the hindfoot and forefoot, plus a separate hallux segment. Although the Oxford Foot Model has been adapted to be used in children, including those with foot deformities due to cerebral palsy, the IOR foot model (Leardini, 2007) is also a good option because it comprises segments for the hindfoot (calcaneus), midfoot (tarsals) and forefoot (metatarsals). The midfoot segment (which is not included in the Oxford Foot Model) allows the measurement between the calcaneus and the tarsals. In the IOR foot model, markers are placed more dorsally on the forefoot because of the clearance in severely deformed gait and to avoid the course of the main foot tendons.

Segment Definition

After defining the marker setup for the gait analysis, it is necessary to build a biomechanical model that allows us to compute all the kinematic and kinetic variables of interest. To do that, each segment of the model needs to be defined in terms of position and orientation. Here is the segment definition used for the CAST marker setup and using Visual 3D software for modelling computation.

Thorax

The thorax segment is built as a rigid segment, from acromium to pelvic markers. Depending on the goal of the gait analysis, sometimes it is not used in the model.

NAME	**PROXIMAL**		**DISTAL**		**TRACKING MARKERS**
THA	**LATERAL**	RASIS	**LATERAL**	RAC	STN1, STN2, STN3, C7
	JOINT		**JOINT**		
	MEDIAL	LASIS	**MEDIAL**	LAC	
	RADIUS		**RADIUS**		

Pelvis

For the pelvis segment, we chose to use the CODA Pelvis as it allows the automatic estimation of the hip joint center (Bell, 1990). Although the functional method has been recommended in literature (Wu, 2002), it is not without limitations, and it requires an adequate range of motion at the hip. Thus, it may be challenging and difficult to implement in children with cerebral palsy, who often have difficulties maintaining balance when standing still, and in actively producing a controlled movement of the lower limb. Within the regression methods used to estimate the hip joint center location, particularly those available in Visual3D, the one used with the CODA Pelvis has shown to perform slightly better when compared to MRI measurements, even in children with cerebral palsy.

NAME	**PROXIMAL**		**DISTAL**		**TRACKING MARKERS**
PELVIS	**LATERAL**	RASIS	**LATERAL**	RPSIS	RASIS, LASIS, RPSIS, LPSIS, RIC, LIC, SAC
	JOINT		**JOINT**		
	MEDIAL	LASIS	**MEDIAL**	LPSIS	
	RADIUS		**RADIUS**		

Thigh

The thigh segment was defined according to the CAST method, as described in Hamill and colleagues (Hamill, 2004). Thus the thigh frontal plane is aligned with the femoral condyles, and its medial/lateral axis falls in this plane and it is perpendicular to the segment's longitudinal axis. Therefore, the medial/lateral axis may not be necessarily parallel to the line that connects the femoral condyles.

NAME	PROXIMAL		DISTAL		TRACKING MARKERS
RTH [LTH]	**LATERAL**		**LATERAL**	RLK [LLK]	RTH1, RTH2, RTH3, RTH4 [LTH1, LTH2, LTH3, LTH4]
	JOINT	RIGHT_HIP [LEFT_HIP]	**JOINT**		
	MEDIAL		**MEDIAL**	RMK [LMK]	
	RADIUS	0.5*DISTANCE (RIGHT_HIP,LEFT_HIP)	**RADIUS**		

Shank

Due to the prevalence of bone deformities, in particular, tibial rotation in children with cerebral palsy, it is recommended to create two different segments for the shank, so that the anatomical axes of the knee and ankle are better represented[1]. However, after comparing the knee angle results when using a proximal shank (frontal plane defined by the lateral and medial femoral condyles and the ankle joint center) and a distal shank (frontal plane defined by the lateral and medial malleoli and the knee joint center), it was observed that the only difference was an offset in the longitudinal axis. When using the proximal shank the longitudinal rotation was close to zero, thus masking the tibial rotation that clinicians expect to see if present. In addition to this and taking into consideration that a segment should be defined using its own bone landmarks, we decided to only create a distal shank. This will also be more coherent with the construction of the thigh (which may also present femoral anteversion) and foot segments. Furthermore, we chose to create this distal shank in agreement with the IOR foot model (Leardini, 2007). Finally, to reduce the amount of tape placed on the child, and to increase consistency when we assess the child with orthoses, we decided to remove the shank cluster, using the following markers as alternatives for tracking: tibial tuberosity (TT), fibula head (FH) and a marker placed on the medial border of the tibia (MBT).

NAME	PROXIMAL		DISTAL		TRACKING MARKERS
RSK [LSK]	**LATERAL**		**LATERAL**	RLA [LLA]	RTT, RFH, RMBT [LTT, LFH, LMBT]
	JOINT	RSK_PROX [LSK_PROX]	**JOINT**		
	MEDIAL		**MEDIAL**	RMA [LMA]	
	RADIUS	DISTANCE(RSK_PROX,RFH) DISTANCE(LSK_PROX,LFH)	**RADIUS**		

Foot

The foot segment is usually represented differently in the context of kinematics and kinetics. Furthermore, in the context of kinematics the foot can be represented as one rigid segment or can be divided into several rigid bodies. With this in mind, we have created 3 different foot segments: a kinematic or virtual foot, a kinetic foot, and a multi-segmented foot.

1. Kinematic foot

Virtual feet are commonly used with the purpose of normalizing the ankle joint angles (i.e. to reduce the inter-subject variability in the standing posture). However, to overcome the inability to create such virtual segment when the neutral posture is compromised, as in the case of children with cerebral palsy, we created a segment (still using the CAST method) which was adapted from other versions of virtual feet and was suggested by the software manufacturers. This segment definition thus forces the horizontal plane of the foot to be aligned with the sole of the patient's foot, and the anterior axis to be aligned with the line going from the midpoint between the malleoli to the midpoint between the 1^{st} and 5^{th} distal metatarsal heads.

NAME	PROXIMAL		DISTAL		EXTRA TARGET	TRACKING MARKERS
VRFT [LVFT]	**LATERAL**		**LATERAL**		**LOCATION**	RD1MT, RD5MT, RHEE, RLCA, RP1MT, RP5MT, RPCA, RSTL, RTOE [LD1MT, LD5MT, LHEE, LLCA, LP1MT, LP5MT, LPCA, LSTL, LTOE]
	JOINT	RANK [LANK]	**JOINT**	RANK_DISTAL [LANK_DISTAL]	ANTERIOR	
	MEDIAL		**MEDIAL**		**TARGET/ LANDMARK**	
	RADIUS	0.01	**RADIUS**	0.01	MID_RMT [MID_LMT]	

2. Kinetic foot

This segment has the same origin and a similar alignment to the kinematic foot, the difference being that it is rotated around the medial-lateral axis, so that the longitudinal axis of the foot is correctly represented for the inverse dynamics calculations. This segment definition is similar to the one described in Hamill (2014), but uses the 1^{st} and 5^{th} metatarsal heads to define the orientation of the frontal plane, as described in Cappozzo (1995), who suggest that the segment's coordinate system should be based on points belonging to that segment only.

NAME	PROXIMAL		DISTAL		TRACKING
RFT [LFT]	**LATERAL**		**LATERAL**	RD5MT [LD5MT]	RD1MT, RD5MT, RHEE, RLCA, RP1MT, RP5MT, RPCA, RSTL, RTOE [LD1MT, LD5MT, LHEE, LLCA, LP1MT, LP5MT, LPCA, LSTL, LTOE]
	JOINT	RANK [LANK]	**JOINT**		
	MEDIAL		**MEDIAL**	RD1MT [LD1MT]	
	RADIUS	0.5*DISTANCE(RLA,RMA) [0.5*DISTANCE(LLA,LMA)]	**RADIUS**		

2.2.2 Markerless Motion Capture Systems

Markerless systems use advanced computer vision and deep learning algorithms to estimate human movement without requiring physical markers. These systems are a convenient alternative to marker-based motion capture systems and use synchronized standard video cameras to estimate anatomic keypoints such as joint centers and other anatomical landmarks for each pose of the subject. Theia3D is a pose estimation software that uses Convolutional Neural Networks and its popularity has been growing in the domain of biomechanics (Kanko, 2021). The following table refers to the main advantages and disadvantages of the current markerless systems.

Advantages	Limitations and considerations
Reduced setup time No need for markers Improved participant comfort Can be used in different environments Can assess multiple subjects at the same time	Accuracy concerns when compared to marker-based systems Not the standard system for clinical gait analysis Not validated for foot deformities and orthoses Assistive devices Light conditions should be good

Setup and Data Collection

Cameras:

- Theia3D requires at least six cameras but recommends the use of at least eight.
- The camera setup should be symmetrical and surround the capture volume (circle, oval, rectangle)
- Cameras should be as close as possible to the capture volume capturing it all
- Avoid filming partial views of subjects, the whole body should be seen by the cameras
- Frame rate depends on the movements to study. Fast movements require high frame rates
- Cameras must be synchronized

Calibration:

- Place a calibration object within the capture volume, at the desired position and orientation to define the global coordinate system.
- Ensure the key points on your calibration object are visible in every camera view, and there are no obstructions.

Data collection:

- Instruct the subject to use appropriate clothing (avoid skirts or clothes that obstruct the visualization of the segments independently – very large clothes are not adequate).
- Ask the subject to perform the gait in the proper location of the laboratory.

2.3 Electromyography

EMG is a technique for measuring muscle response or electrical activity in response to a nerve's stimulation of the muscle. There are primarily two types of EMG commonly used: surface EMG, a non-medical procedure in which electrodes are placed on the skin's surface, and intramuscular EMG, which is carried out using a needle electrode or a needle containing two fine-wire electrodes inserted directly into a muscle. When a muscle contracts, it generates an electrical current known as action potentials that travels through the muscle tissue and is detected by the electrodes. Muscle contraction is, therefore, measured by detecting the potential difference between two electrodes. The most used technique for gait analysis is surface EMG.

2.3.1 Skin Preparation

The need to reduce the skin-electrode impedance has been diminished due to the high input impedance offered by today's amplifiers. Techniques that require abrasion with fine sandpaper or similar materials are now largely redundant, but some skin preparation is still required[18]. Delsys' recommendations are:

1. Shave if excessive hair is present to allow a stronger bond with the skin.
2. Dab the skin with medical tape to dislodge excessive dry skin cells.
3. Wipe the skin with isopropyl alcohol to remove oils and surface residues (and any adhesive residue that may remain, if applicable).

2.3.2 Electrodes Placement and data collection

Delsys Trigno wireless sensors were chosen to collect the EMG signal due to their type (bipolar), characteristics and configuration. Bipolar EMG systems are preferred over monopolar systems for their greater stability and selectivity. Furthermore, bipolar EMG systems are a better choice for nonisometric contractions and allow the use of differential amplification and common mode rejection. De Luca (2003) recommends the use of silver bar electrodes that are 10mm long, 1mm wide and have a distance of 10mm between them, as this inter-electrode distance will result in a bandwidth that contains the full frequency spectrum of the raw EMG. Furthermore, this inter-electrode distance is fixed in the Trigno sensors, thus removing variability from this source of error in different measurements. Additionally, movement artifact is also reduced due to the removal of wires connected to the sensors.

A generally accepted recommendation is to place the electrodes in the middle of the muscles' belly when contracted. Most of times this will avoid placing the electrodes on top of a motor point, but it is not guaranteed. Thus we take into account this general recommendation as well as the recommended guidelines suggested by the Seniam and Criswell (2011). Additionally, these guidelines are complemented with a good knowledge of musculoskeletal anatomy and confirmation of the correct sensor location via voluntary contraction and palpation of the muscle of interest. Furthermore, the orientation of the sensor is also important. The sensor should be aligned with the muscle fibers, otherwise the amplitude of the signal may be reduced by as much as 50% (De Luca, 2003). Depending on the level of impairment of the participant, the muscles that should be assessed may be different. The main muscles of the lower limb that are assessed in a clinical gait analysis are: gluteus maximus, gluteus medius, adductor longus, rectus femoris, biceps femoris, tibialis anterior and gastrocnemius. Usually, before each session, a few steps should be followed:

1. prepare 12 sensors fully charged (This is for 12 muscles. Prepare more to add more muscles).
2. Check the channels in the EMG board and the connection with the motion caption system. Set each channel with the muscle name or take note of the sensor number and the respective muscle.
3. After placing the sensors in the participant, test each one, by asking the person to perform a specific movement (for instance, to test gastrocnemius muscle, ask the participant to do plantarflexion, preferably against some resistance).

3 Musculoskeletal Modelling

(Filipa João, Raquel Costa, Carolina Silva)

Musculoskeletal modelling is a computational technique used to study the mechanics and function of the human musculoskeletal system in a non-invasive way. It involves mathematical models that simulate the interaction between bones, joints, muscles, and tendons, to analyze variables such as joint contact forces, muscle contributions to centre of mass acceleration, and muscle forces and activations. This approach may help improve strategies to prevent or rehabilitate musculoskeletal disorders, as well as predict surgery outcomes, making it a valuable tool for clinical decision-making.

OpenSim

OpenSim (Delp, 2007) is an open-source musculoskeletal simulation software for modelling, simulating, and evaluating the neuromusculoskeletal system. It offers advanced tools for running dynamic simulations of movement, while encouraging multidisciplinary research within the biomechanics community.

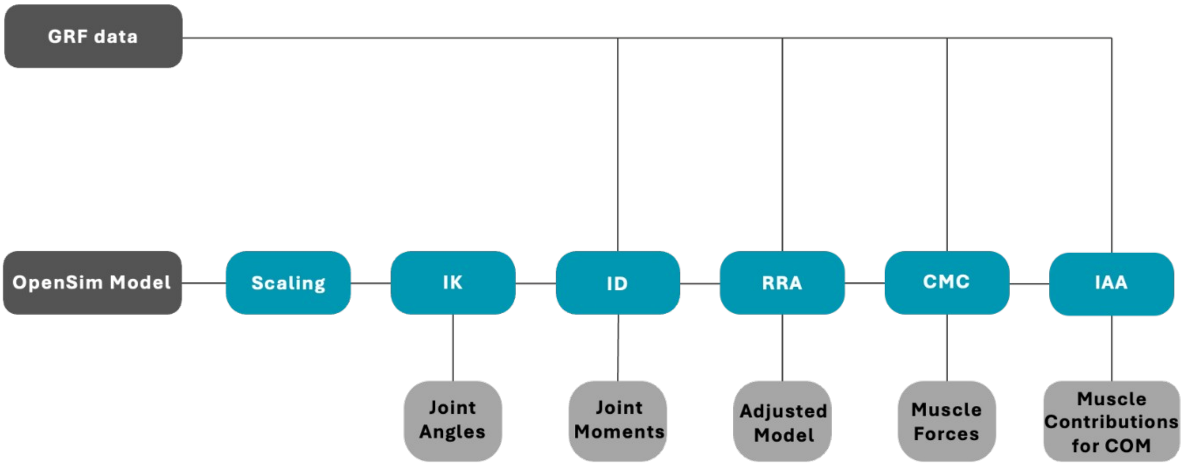


Figure X: Example of an OpenSim pipeline, including the tools, their main inputs and outputs. Dark grey illustrates the inputs. Blue represents the tools, namely scaling, IK (Inverse Kinematics), ID (Inverse Dynamics), RRA (Residual Reduction Algorithm), CMC (Computed Muscle Control), and IAA (Induced Acceleration Analysis). The main outputs from each tool are presented in light grey.

Some common techniques adopted in clinical application are muscle length. Muscle length is calculated with the scaling of the origin and insertion of a muscle based on segment's length and is defined by the distance between these two points. The information that muscle length gives is similar to what happens with a joint angle but in biarticular muscles, like rectus femoris for instance, it is useful to plot it because knee or hip joint angles alone may not reveal what is really happening with muscle length.

4. Questionnaires

(Filomena Carnide, Vera Moniz Pereira)

Part of the clinical gait assessment comprises the gathering of relevant information about the participant. There are different questionnaires especially developed to be applied to children with cerebral palsy. Those questionnaires have as main outcome measures of performance, functionality, independence, comfort, communication, social participation, physical and psychological aspects of the participant, quality of life and wellbeing. This is important to assess due to the multidisciplinary team that is involved with each participant, in order to improve the decision making process along with the other assessments. The following table shows the main questionnaires used to assess cerebral palsy participants, their psychometric properties, outcome measures, administration procedures and validation for European Portuguese language.

Tool name:	**References:**	**Target population:**	**Outcome measures:**	**Administration:** (who, where and duration)	
ASK-Activities Scale for Kids	Cavalheiro, L. M., Paixão, D., Gonçalves, R. S., & Ferreira, P. L. (2014). Measuring health-related quality of life in Children: reliability and validity of the Portuguese version of the Activities Scale for Kids (ASK) (p. 1). Plint, A. C., Gaboury, I., Owen, J., & Young, N. L. (2003). Activities scale for kids: an analysis of normals. Journal of Pediatric Orthopedics, 23(6), 788–790. doi:10.1097/01241398-200311000-00018	Children aged 5–15 years.	Performance, Capacity.	**Who:** Children up to 10 years old should respond independently but with the presence of a caregiver, parent, or physiotherapist to clarify concepts or meanings if needed. Children aged 10 and older should read and respond on their own. **Where:** At home or during a physiotherapy session. **Duration:** 5–9 minutes.	X X X X X X

Tool name:	**References:**	**Target population:**	**Outcome measures:**	**Administration:** (who, where and duration)	

CCHQ (The Care and Comfort Hypertonicity Questionnaire)	Stacey Carlon1, N. S., Yong, K., Gilmore, R., Sakzewski, L., & Boyd, R. (2010). A systematic review of the psychometric properties of Quality of Life measures for school aged children with cerebral palsy. p. 6	Caregivers/parents of children with moderate to severe cerebral palsy.	Personal care; positioning/transfers; comfort and interaction/communication.	**Who:** Filled out by the caregiver. **Duration:** 10 minutes.	 x x x x

Tool name:	References:	Target population:	Outcome measures:	Administration: (who, where and duration)	
CHQ	Stacey Carlon1, N. S., Yong, K., Gilmore, R., Sakzewski, L., & Boyd, R. (2010). A systematic review of the psychometric properties of Quality of Life measures for school aged children with cerebral palsy. p. 6	Children aged 5-18 years.	Physical and psychological aspects.	Self-completion version for children (87 items – 16 to 25 minutes) and self-completion version for parents with 28 items (5 to 10 minutes) or 50 items (10 to 15 minutes).	X X X X

Tool name:	References:	Target population:	Outcome measures:	Administration: (who, where and duration)	Psycho	
Cerebral Palsy Quality of Life Questionnaire for Children	M. P., Braccialli, A. C., Sankako, A. N., Luiza, M., & Almeida, S. (2013). Quality of Life Questionnaire for Children With Cerebral Palsy (Cp Qol-Child): Translation and Cultural Adaptation for Bra. Journal of Human Growth and Development, 23(2), 1–10. Chen, K. L., Wang, H. Y., Tseng, M. H., Shieh, J. Y., Lu, L., Yao, K. P. G., & Huang, C. Y. (2013). The Cerebral Palsy Quality of Life for Children (CP QOL-Child): Evidence of construct validity. Research in Developmental Disabilities, 34(17), 994–1000. doi:10.1016/j.ridd.2012.11.025 Wang, H., Cheng, C., Hung, J., & Ju, Y. (2010). Neuropsychological Rehabilitation : An International Validating the Cerebral Palsy Quality of Life for	Children with cerebral palsy aged 4-12 years	7 domains of quality of life: well-being and social acceptance; feelings about functionality; social participation, physical health and emotional well-being, and pain.	**Who:** Completed by caregivers (for children aged 4 to 12 years) Completed by children ages 9 to 12 years. **Duration:** 15 to 25 minutes.		Interrater
					X	Test-retest
					X	Internal co
						Concurrer

	Children (CP QOL-Child) questionnaire for use in Chinese populations, (November 2014), 883–898. doi:10.1080/09602011.2010.509190					
					X	Construct validit CP QOL-CHILD moderadamente com QV para a v cuidadores (r=0. crianças (r=0.41- saúde global (cui 0.56 e crianças r=
						Os mesmos dom moderamente co com a KIDSCRE 0.51),excepto na impacto da defic também correlac versão de auto p (r=0.61 –0.70).
						A correlação ent CHILD e CHQ é nos diversos dom moderamente co

Tool name:	References:	Target population:	Outcome measures:	Administration: (who, where and duration)	Psy	
CP-Child	Narayanan, U. G., Weir, S., & Fehlings, D. L. (2007). CPCHILD - Caregiver Priorities and Child Health Index of Life with Disabilities (CPCHILD©) Questionnaire. pp. 10-29.	Directed towards caregivers (with children with CP between 5-12 years old).	Personal care; positioning; transfer and mobility; emotions and behavior; communication and social interaction; health; overall quality of life.	It takes between 20-30 minutes to be completed by parents or caregivers of children with severe developmental disabilities, such as those with cerebral palsy in a non-ambulatory condition. When the child is able to communicate, the questionnaire should be completed by both (child and parents/caregivers). The questionnaire should be filled out at home or during a clinical visit		
					x	r
					x	T r
					x	co
						C
					x	Con vali
						Disc vali
						Resp

Tool name:	References:	Target population:	Outcome measures:	Administration: (who, where and duration)	Psychometric properties:			Validated in European Portuguese?
Disabkids (genérico)	DisabKids. (s.d.). DisabKids. Obtido em 8 de janeiro de 2015, de DISABKIDS Chronic Generic Measure - DCGM-37 (long version). Simeoni MC, Schmidt S, Muehlan H, Debensason D, Bullinger M,	Children with cerebral palsy aged 8-16 years.	Quality of life - 37 items in the following domains: independence; emotions; inclusion; exclusion; limitations; and medication.	Self-completion version for children and self-completion version for parents (n/d time).				No
						Interrater reliability:	ICC or Kappa: 0,74-0,93	
						Test-retest reliability:	ICC or Kappa: 0,97	
						Internal	Cronbach's	

	Group TD. Field testing of a European quality of life instrument for children and adolescents with chronic conditions: the 37-item DISABKIDS Chronic Generic Module. Quality of Life Research. 2007; 16(5): 881-93.					consistency:	alpha: 95%	
						Concurrent validity:	R or Rho:	
						Construct validity	Eigenvalue: Cuidados pessoais: 0,607; Mobilidade: 0,619; Interação social: 0,518	
						Discriminative validity:	R or Rho:	
						Responsiveness:	Effect size:	

Tool name:	**References:**	**Target population:**	**Outcome measures:**	**Administration: (who, where and duration)**	**Psychometric properties:**			**Validated in European Portuguese?**
KIDSCREEN 52 - Health Related Quality of Life Questionnaire for Children and Young People and their Parents (versão para preenchimento das Crianças e adolescentes e versão para os Pais)	Gaspar, T., & Matos, M. G. (2008). Qualidade de Vida em Crianças e Adolescentes Versão Portugues dos Instrumentos Kidscreen-52. Behaviour (p. 125). Retrieved from http://enspt.fmh.utl.pt/aventurasocial/pdf/Qualidade.de.Vida.KIDSCREEN.pdf	Children and adolescents aged 8-18 years and parents.	Health and Physical Activity; Feelings; General Mood State; Self-Perception; Leisure Time; Family and Family Environment; Economic Issues; Friends; School Environment and Learning; Bullying.	**Who:** Children and parents **Where:** Hospitals, medical establishments, schools **Duration:** 10-15 minutes				No
						Interrater reliability:	ICC or Kappa:	
						Test-retest reliability:	ICC or Kappa:	
					X	Internal consistency:	Cronbach's alpha: 0,60-0,88	
						Concurrent validity:	R or Rho:	
						Construct validity	Eigenvalue:	
						Discriminative validity:	R or Rho:	
						Responsiveness:	Effect size:	

Tool name:	**References:**	**Target population:**	**Outcome measures:**	**Administration: (who, where and duration)**	**Psychometric properties:**			**Validated in European Portuguese?**
Pediatric Quality of Life Inventory — PedsQL 4.0	(Varni, Burwinkle, Seid, & Skarr, 2003)	Children and adolescents aged 2-18 years.	**Health-related Quality of Life (HRQL):** assesses the impact of health studies and treatments on the patient's life and well-being. It evaluates physical, emotional, social function, and school performance.	**Who:** Completed by the child/adolescent (aged 5 to 18 years)				Yes
						Interrater reliability:	ICC or Kappa:	
						Test-retest reliability:	ICC or Kappa:	
					X	Internal consistency:	Cronbach's alpha:	

				Completed by parents/caregivers (for ages 2 to 18 years). **Duration:** 5 minutes.		Concurrent validity:	Child self-report, 5-7 years (0.86); 8-12 years (0.91); 13-18 years (0.91)	
					X	Construct validity	Parent report, 2-4 years (0.89); 5-7 years (0.91); 8- 12 years (0.92); 13-18 years (0.92)	
						Discriminative validity:	R or Rho:	
						Responsiveness:	Eigenvalue:	

Tool name:	**References:**	**Target population:**	**Outcome measures:**	**Administration:** **(who, where and duration)**	**Psychometric propert**		
TNO AZL TACQOL Questionnaire for Children's Health related Quality of Life	Verrips, E., Vogel, H., Theunissen, N., Kamphuis, R. O. B. P., Fekkes, M., Wit, J. a N. M., & Verloove-vanhorick, S. P. (1988). Measuring health-related quality of life in a child population. International Child Health, 188–193. doi:10.1093/eurpub/9.3.188	Children with chronic diseases aged 6-15 years and parents.	Physical complaints and motor functioning (physical), autonomous functioning (daily living), social functioning	**Who:** Children themselves or by the parents. **Duration:** 10-15 minutes.	PF - Parent Form		
					X	Interrater reliability:	ICC or 0,87 –
					X	Test-retest reliability:	ICC or 0,39 –
					X	Internal consistency:	Cronb alpha: 0,84
						Concurrent validity:	R or R
						Construct validity	Eigenv
						Discriminative validity:	R or R
					X	Responsiveness:	Effect
					CF – Child Form		
					X	Interrater reliability:	ICC or 0,83 –
					X	Test-retest reliability:	ICC or 0,39 –
					X	Internal consistency:	Cronb alpha: 79
						Concurrent validity:	R or R
						Construct validity	Eigenv

						Discriminative validity:	R or R
						Responsiveness:	Effect

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Appendix

APPENDIX 1 – MODIFIED ASHWORTH SCALE (Bohannon & Smith, 1987; Mutlu et al., 2008)

It is a qualitative scale aimed at assessing muscle tone in individuals with central nervous system dysfunction.

MODIFIED ASHWORTH SCALE	
1	No increase in muscle tone.
2	Slight increase in tone, manifested by a catch and release or by minimal resistance at the end of motion when affected part is moved in flexion or extension.
1+	Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the range of motion.
2	More marked increase in muscle tone through most of the range of motion, but affected part easily moved.
3	Considerable increase in muscle tone, passive movement difficult.
4	Affected joints rigid in flexion or extension.

APPENDIX 2 – MODIFIED OXFORD SCALE (Council, 1943; Kendall & Kendall, 1949)

MODIFIED OXFORD SCALE	
0	No muscle contraction detected (palpable or visible).
1	Palpable or observable flickers of muscle activity but no movement.
2	Can move through available range with gravity eliminated (cannot overcome gravity).
3	Overcomes gravity throughout the available range.
3+	Overcomes gravity and mild resistance.
4	Overcomes gravity and moderate resistance.
4+	Overcomes gravity and strong resistance.
5	Overcomes gravity and all resistance – normal muscle strength.

APPENDIX 3 – MODIFIED BOYD and GRAHAM SCALE FOR SELECTIVE MOTOR CONTROL (Boyd & Graham, 1999)

Definition	Grade
No movement when asked to perform an isolated joint movement	0
Initiation of movement at the test joint performed primarily with muscles other than prime movers with only abnormal synergy (no isolated movement at the test joint)	1
Isolated movement at the test joint performed with prime movers through less than half of the available range of motion followed by abnormal synergy	2
Isolated movement at the test joint performed with prime movers through more than half of the available range of motion followed by abnormal synergy	3
Isolated movement at the test joint through full available range accompanied by impairment in	3+

smoothness or timing of movement but without abnormal synergy	
Isolated movement at the test joint through full available range of motion with smooth, continuous movement and normal timing. No abnormal synergy	4