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Análisis de la cinemática y la simetría de la marcha humana en pacientes con hemiparesia utilizando un dispositivo de retroalimentación auditiva

Gait kinematics and symmetry in patients with hemiparesis using an audio feedback device

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Gait kinematics and symmetry in Patients with Hemiparesis using an Audio Feedback Device

Summary

The symmetry is an important gait feature that is measured and reported frequently, particularly in patients with hemiparesis. For many rehabilitation professionals a goal of gait re-education is the achievement of symmetry during locomotion.

The purpose of the study is to examine changes in gait symmetry following the training with an audio feedback device in patients with hemiparesis. The project has been developed in collaboration with Sant Joan de Déu Hospital (HSJD) that has provided with the patients involved in the study. Gait analysis was acquired in the Biomechanics Laboratory of the Technical University of Catalonia (UPC) using an optical system and the kinematic analysis was performed using the software OpenSim.

The audio feedback device (Walking o'clock) evaluated is a prototype developed by a Spanish company. The device contains an inertial measurement unit (IMU) to measure the absolute angle of a segment, and it is connected via wi-fi to a computer where the therapist can see the value. Walking o'clock is placed on both tights of the patients with a velcro strap and it makes a sound when it reaches a threshold value. This value is selected by the therapist according to the gait pattern that he wants to correct.

Through a kinematic analysis we will try to check if the use of this audio feedback device produces changes in the symmetry of gait. For this purpose, joint angles, range of motion, angular velocity and eight spatiotemporal parameters have been calculated and analyzed for four patients with hemiparesis.

From the results, it was shown that the device decreases the asymmetry of some gait parameters, but at the same time increases it in others. There are factors that influence the response to feedback such as the instruction given to the patient, the selection of the threshold angle, and the training time with the device.

This report describes all the processes involved in the analysis, as well as the methodology used. A biomechanical human model was developed to reproduce the motion as close to reality as possible using the software OpenSim. Then, an inverse kinematic analysis was implemented to obtain the range of motion of the joints produced by the patient during the gait cycle. Also, an analysis of the spatiotemporal parameters was included in the study.

Resumen

La simetría es una característica importante de la marcha humana analizada con frecuencia en pacientes con hemiparesia. Para muchos profesionales de la rehabilitación el objetivo final de la terapia con este tipo de pacientes es alcanzar la mayor simetría posible en la marcha.

El objetivo del presente estudio es comprobar si existen cambios en la simetría de la marcha utilizando un dispositivo con feedback auditivo en pacientes con hemiparesis. El proyecto ha sido desarrollado en colaboración con el Hospital Sant Joan de Déu (HSJD) de la ciudad de Barcelona, el cual ha brindado a los pacientes que participan en el estudio. La adquisición de los datos cinemáticos ha sido realizada en el Laboratorio de Biomecánica de la Universidad Politécnica de Cataluña (UPC) utilizando el sistema óptico de capturas compuesto por 16 cámaras de infrarrojos y un software de análisis de movimiento propio del sistema. Para el posterior análisis y procesamiento de los datos se utilizó el software libre de simulación biomecánica OpenSim desarrollado por la Universidad de Stanford y ampliamente utilizado en la comunidad científica internacional. También se utilizó el software Matlab en el tratamiento de los datos analizados.

El dispositivo utilizado en las pruebas es un prototipo desarrollado por una empresa española que se encuentra trabajando actualmente en colaboración con el HSJD. El dispositivo permite obtener una medida del ángulo absoluto del segmento en el que se coloca. Se encuentra diseñado para que realice un feedback auditivo cuando mida un ángulo absoluto seleccionado como umbral.

En el estudio participaron 4 pacientes con hemiparesia, los cuales fueron seleccionados por el equipo de terapistas del hospital. La metodología de captura en el laboratorio con el objetivo de validar la respuesta del paciente ante el uso del dispositivo se dividió en 4 escenarios:

1. Natural: durante esta prueba se colocó un dispositivo en cada muslo del paciente pero sin activar aún el feedback auditivo. Se le pidió que realice una marcha normal a una velocidad que le resulte cómoda en el espacio de captura visualizado por el sistema de cámaras del laboratorio. En este momento se realizan dos mediciones independientes una de la otra: por una parte se captura la marcha natural del paciente con el sistema de cámaras del laboratorio; y por otra parte los dispositivos miden la máxima flexión y extensión de la cadera, calculadas a partir del movimiento del muslo.

2. Feedback: durante esta prueba el fisioterapeuta debe decidir cuál es el rango de movimiento que quiere modificar y en base a esto elige el ángulo que será utilizado como umbral para realizar el feedback auditivo. El fisioterapeuta compara los valores de una pierna y de la otra, y decide un valor de ángulo que

será el umbral para que el dispositivo emita el sonido. Se le pide al paciente que levante la pierna hasta escuchar el feedback y en ese momento bajarla para continuar el paso. En este momento se mide al paciente utilizando el feedback con el sistema de cámaras del laboratorio.

3. After Feedback Inmediate (AFI): se le pide al paciente que entrene con el feedback auditivo 10 minutos. Luego se quita el sonido y se le pide al paciente que vuelva a caminar, capturando el patrón de marcha realizado sin feedback después de haber entrenado durante 10 minutos con el feedback.

4. After Feedback Training (AFT): se le pide al paciente que descanse durante 5 minutos y se vuelve a repetir la captura de la marcha. Estos 2 últimos escenarios pretender comprobar si la información otorgada por el feedback fue incorporada por el paciente en su patrón de marcha a pesar de no escuchar más el feedback auditivo.

La idea del sistema es que el modelo final del dispositivo pueda ser utilizado por el paciente fuera de la terapia brindando una mayor continuidad a su rehabilitación. Una vez establecido el umbral adecuado para el feedback, según la necesidad de cada paciente, el dispositivo podría ser utilizado por el paciente de forma independiente y en cualquier sitio.

Después de realizar las mediciones en los 4 pacientes seleccionados se procedió a realizar el procesamiento y análisis de los datos obtenidos durante las pruebas. Con el objetivo de comprobar cambios en la simetría de la marcha entre los distintos escenarios explicados anteriormente, se realizó el cálculo de ocho parámetros espaciotemporales de la marcha y los rangos de movimiento alcanzados en pelvis, cadera, rodilla y tobillo en el plano sagital.

Un estudio previo realizado con el mismo equipo de trabajo realizó un procedimiento similar comprobando que el dispositivo de feedback auditivo realizaba cambios en los rangos articulares de los pacientes analizados (N=3). El presente trabajo adiciona la medición de los parámetros espaciotemporales y realiza análisis enfocados a comprobar cambios en la simetría de la marcha, comparando los parámetros medidos en el lado no afectado con los medidos en el lado afectado.

Contents

1. Introduction

1.1 Motivation

The present work, “Gait kinematics and symmetry in Patients with Hemiparesis using an Audio Feedback Device”, corresponds to the Master Thesis of Biomedical Engineering, and has been developed at the Biomechanical Engineering Group (BIOMEC) in the Department of Mechanical Engineering at the School of Industrial Engineering of Barcelona (ETSEIB). The group belongs to the Biomedical Engineering Research Centre (CREB) of the Universitat Politècnica de Catalunya (UPC).

The main motivation of the author is the development of the multidisciplinary work applied to the neurorehabilitation. It is essential that biomedical engineers work together whit physicians and physiotherapist to achieve a common goal. Otherwise, the development will be tested in the laboratory but it will never be implemented.

Fortunately, this project is an interdisciplinary work developed in collaboration with Sant Joan de Déu Hospital (HSJD) that has provided with the patients involved in the study, and with company Draco Systems, who has designed the audio feedback device used in the study. Moreover this project is a continuation of a previous study developed with the same work team. According to the Research Team of HSJD, the presented work extends the previous study including new symmetry parameters.

The main objective of the project is to examine changes in gait symmetry of patient with hemiparesis following the training with an audio feedback device. This device is a prototype called Walking o’clock, developed by a Spanish company Draco Systems and it will be explained in detail further in this work.

The biomechanical study allows us to analyze if there are changes in the symmetry gait of the patients when they use the device. The parameters that will be analyzed are: sagittal plane joint angles of pelvis, hip, knee and ankle, cycle time, stance time, swing time, cadence, stride length, step length, step width and walking speed.

Walking o’clock pretend to be a tool to support the rehabilitation of gait and that patients can use by itself anywhere. The study developed in the BIOMEC laboratory validates the operation of this device due to it shows if the device produces change in the gait kinematic parameters and symmetry.

1.2 Objectives

The main goal of the study is to show if the device Walking o’clock produces improvements in the gait pattern of four children patients with hemiparesis. For this purpose, the development of a human biomechanical model is needed.

The biomechanical model allows knowing the position of the anatomical segments and the topological structure of the human body. As a result, it is possible to obtain quantitative information of the skeletal structure movement and the resultant joint torques that involved muscles produce along the gait cycle.

The main goal is accomplished by means of the following specific objectives:

- Performing biomechanical studies of four pediatric patients with hemiparesis using the UPC Biomechanics Laboratory in four different scenarios: gait without device, gait using the device, gait after training using the device for 10 minutes and gait after resting 5 minutes.
- Developing a biomechanical human model that reproduces the motion as close to reality as possible.
- Implementing an inverse kinematic analysis to obtain the range of motion of the joints produced by the patient during the gait cycle.
- Analyzing spatiotemporal parameters in the four different scenarios.
- Comparing the result of kinematics variables of the gait in the four different scenarios for each patient.
- Analyzing the variables associated with symmetry

2. Background

2.1 Biomechanics of human gait

Gait kinematics is a general term that refers to the measurement of the linear and angular displacement, the velocity and the acceleration of the body segments throughout the gait cycle.

Usually, any movement event could be chosen to define the gait cycle it is identified as the time period during locomotion in which one foot contacts the ground until when the same foot contacts again the ground.

Normal people initiate floor contact with their heel (heel strike). However we should take into consideration that people with a pathological gait could initiate floor contact with another part of their foot, therefore the initial contact (IC) is the generic term for designating the onset of the gait cycle (Figure 1).

2.1.1 Phases of Gait

Traditionally, the gait cycle has been divided into five stance phase periods and three swing phase periods [1]. This is known as Ranchos classification because it was developed by Ranchos Los Amigos hospital in Los Angeles.

An alternative classification [2] defines three periods of stance: initial double support, single limb stance, and second double support. A more functional classification [3] divides the cycle based on the task being performed during each sub-phase.

In the present work Ranchos classification is used (Figure 1):

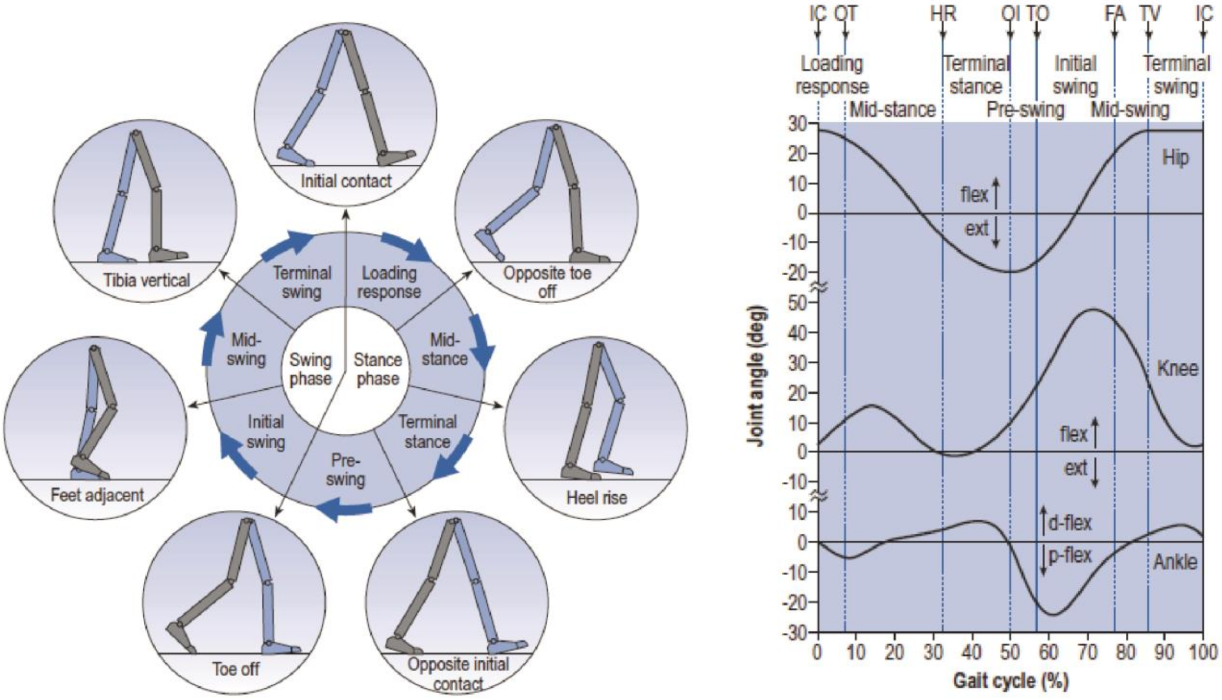


Figure 1. Left: Positions of the legs during a single gait cycle by the right leg (gray). Right: Sagittal plane joint angles (degrees) during a single gait cycle of right hip (flexion positive), knee (flexion positive) and ankle (dorsiflexion positive). IC = initial contact; OT =opposite toe off; HR = heel rise; OI =opposite initial contact; TO = toe off; FA= feet adjacent; TV = tibia vertical. [Whittle, 2002]

In the gait cycle classification developed by [1] the stance phase, which is also called the 'support phase' or 'contact phase', lasts from initial contact to toe off. It is subdivided into:

Loading response: The loading response is the double support period between initial contact and opposite toe off. During this period, the foot is lowered to the ground by plantar flexion of the ankle. The hip begins to extend, the knee is in a nearly fully extended position at initial contact and flexes during loading response.

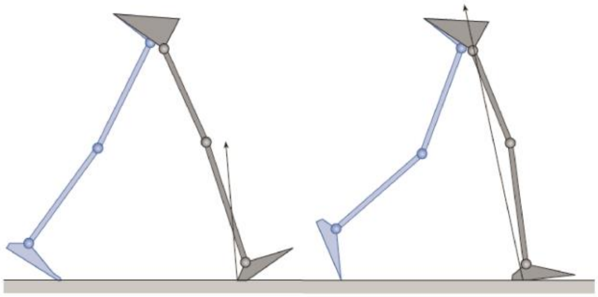


Figure 2. Loading response. [2]

Mid-stance: is the period of the gait cycle between opposite toe off and heel rise. This is the first half of the single limb support interval and it occupies the period from 7% to 32% of the cycle. The hip goes from being flexed to being extended. The knee reaches its peak of stance phase flexion and starts to extend again, the peak generally occurs at between 10% and 20% of the gait cycle. The ankle angle changes from plantarflexion to dorsiflexion.

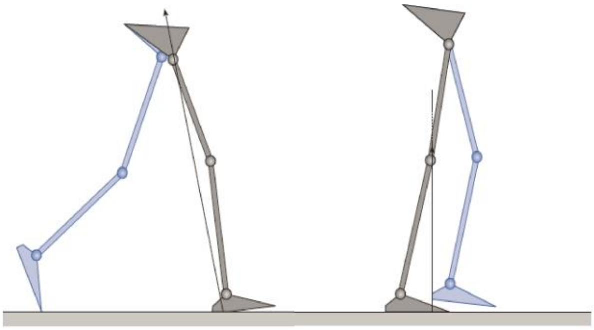


Figure 3. Mid-stance. [2]

Terminal stance: this phase completes single limb support. It begins with heel rise and continues until the other foot strikes the ground. The knee increases its extension and then just begins to flex slightly. Increased hip extension and the other limb (blue) are in terminal swing.

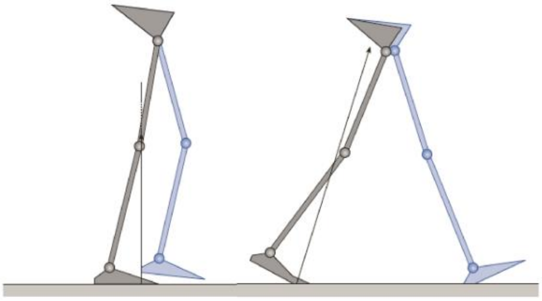


Figure 4. Terminal stance. [2]

Pre-swing: it begins with initial contact of the opposite limb and ends with toe off. This final phase of stance is the second double stance interval in the gait cycle. Some researchers call "weight transfer" at this phase. The reference limb (gray) responds with increased ankle plantarflexion, greater knee flexion and loss of hip extension.

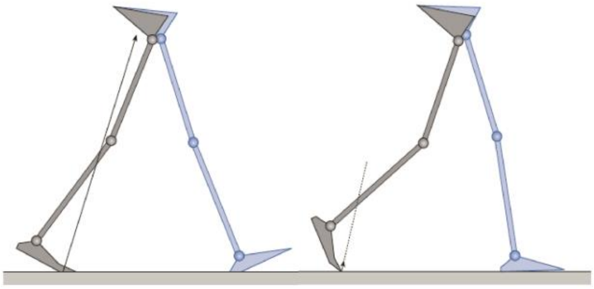


Figure 5: Pre swing. [2]

The swing phase lasts from toe off to the next initial contact.

It is subdivided into:

Initial swing: it begins with toe off and ends when the swinging leg passes the stance phase leg and the two feet are side by side. The foot is lifted and limb is advanced by hip flexion and increased knee flexion. The ankle is partially dorsiflexed.

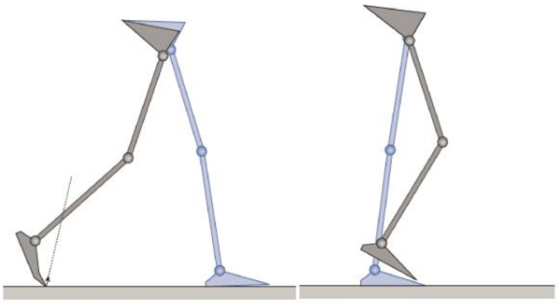


Figure 6: Initial swing. [2]

Mid-swing: it begins when the swinging limb is opposite the stance limb and it ends when the swinging limb is forward and the tibia is vertical. In this phase, the hip is flexed, the knee is extended and the ankle continues dorsiflexing to neutral.

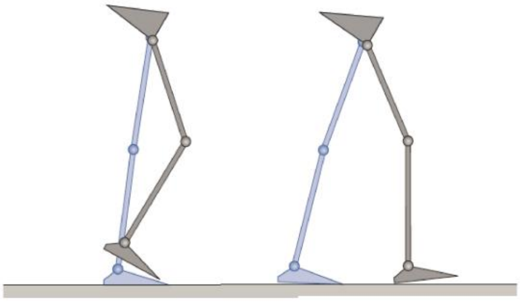


Figure 7: Mid-swing. [2]

Terminal swing: is the final phase of swing, it begins with a vertical tibia and ends when the foot strikes the floor. Limb advancement is completed by knee extension. The hip maintains its earlier flexion and the ankle remains dorsiflexed to neutral.

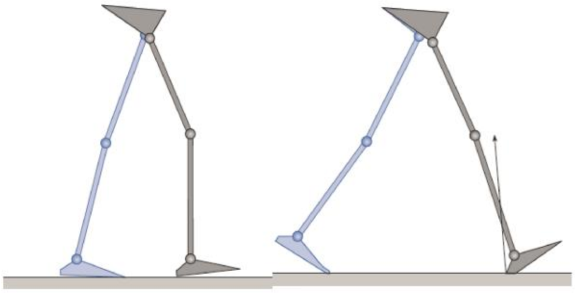


Figure 8: Terminal swing. [2]

2.1.2 Gait cycle timing

With regard to the duration of a complete gait cycle, each gait cycle is divided into two periods, stance and swing. *Stance* is the term used to designate the entire period during which the foot is on the ground. Stance phase begins whit initial contact. The word *swing* applies to the time the foot is in the air for limb advancement and the swing phase begins as the foot is lifted from the floor (toe-off), (Perry J., 1992).

Figure 9 show the timings of initial contact and toe off for both feet during a little more than one gait cycle. Right initial contact occurs while the left foot is still on the ground and there is a period of *Double support* between initial contact on the right and toe off on the left. During the swing phase on the left side, only the right foot is on the ground, giving a period of *right single support*, which ends with initial contact by the left foot. There is then another period of double support, until toe off on the right side. *Left single support* corresponds to the right swing phase and the cycle ends with the next initial contact on the right.

In each gait cycle, there are thus two periods of double support and two periods of single support. The stance phase usually lasts about 60% of the cycle, the swing phase about 40% and each period of double support about 10%.

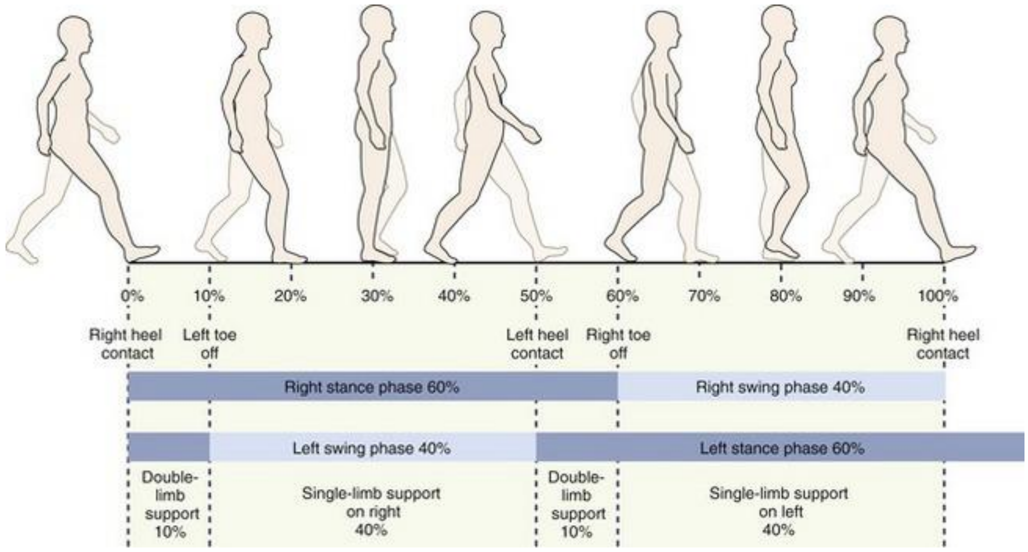


Figure 9. Timing of single and double support during a little more than one gait cycle, starting with right initial contact. [4]

2.1.3 Foot placement

Figure 10 shows the terms used to describe the placement of the feet on the ground. The stride length is the distance between two successive placements of the same foot. It consists of two step lengths, left and right.

In the pathological gait, it is common for the two step lengths to be different. If the left foot is moved forward to take a step and the right one is brought up beside it, rather than in front of it, the right step length will be zero.

The Figure 10 shows other important parameters like *walking base* and *toe out*. *Walking base* or *stride width* or *base of support* is the side to side distance between the line of the two feet, usually measured at the midpoint of the heel, but sometimes the center of the ankle joint. This parameter allows analyzing the balance.

Toe out is the angle in degrees between the direction of progression and a reference line on the sole of the foot.

When a pathology affects one foot more than the other, the subject will usually try to spend a shorter time on the ‘bad’ foot. The stance phase will be shorter on the affected side and, in consequence the duration of the swing phase and the step length on the non-affected side will be reduced. Thus, a short step length on one side generally means problems with single support on the other side. [2]

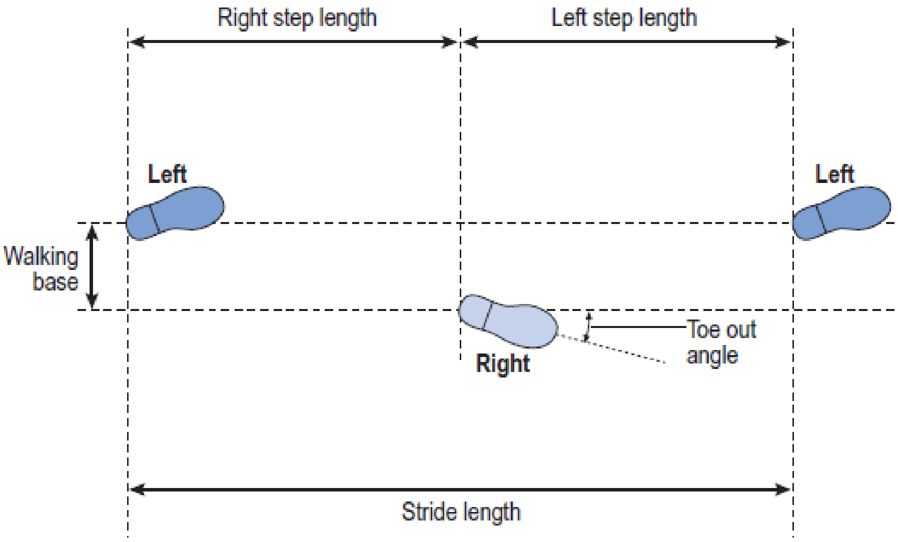


Figure 10. Foot placement on the ground. Taken from Whittle, 2002

2.1.4 Joint angles

Generally, the gait kinematics is expressed in terms of the joint angles between each limb segment. These quantities are most often described three-dimensionally using anatomical planes relative to the more proximal segment, but also include the global position of the pelvis relative to a fixed laboratory coordinate system.

Generally, the *knee* angle is defined as the angle between the femur and the tibia. The *ankle* angle is usually defined as the angle between the tibia and a line in the foot. Although this angle is normally around 90°, it is conventional to define it as 0°, dorsiflexion and plantarflexion being movements in the positive and negative directions. In this work, dorsiflexion is a positive angle. The *hip* angle is the angle between the pelvis and the femur.

During gait, important movements occur in all three planes: sagittal, frontal and transverse (Figure 11). However, the sagittal plane is the most studied and physiotherapists are more familiar with the graphics on this plane (column 1 of Figure 11).

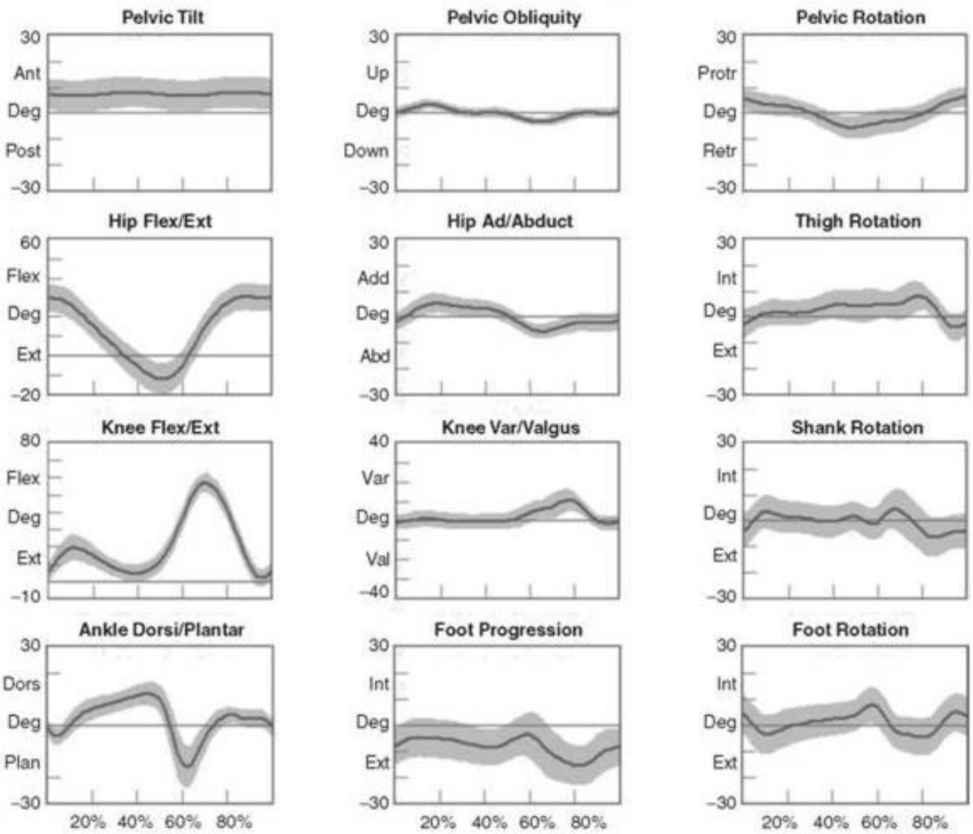


Figure 11. Columns from left to right: sagittal, frontal and transverse joint angles during a single gait cycle of pelvic tilt and right hip, knee and ankle.[5]

2.2 Pathological Gait

The pattern of gait is the outcome of a complex interaction between the many neuromuscular and structural elements of the locomotor system. Abnormal gait may result from a disorder in any part of this system, including the brain, spinal cord, nerves, muscles, joints and skeleton. Spastic hemiplegia is the most common neurological cause of an abnormal gait [2]. The word hemiplegia means the neuromuscular disorder that involves one-half of the body in the frontal plane while the other half is normal or near normal. As well as occurring in cerebral palsy, it is also frequently seen in elderly people who have had a cerebrovascular accident and may also occur following traumatic brain injury.

The study developed in the present work involves patient with hemiparesis, due to the abnormal gait patterns associated with this condition will be explained in detail further in the next section.

2.2.1 Hemiparesis

The hemiparetic gait is described as being slow, laborious and abrupt. This alteration is due to deficiencies in perception-cognition, motor control, joint mobility, strength and muscle tone. The hemiparetic gait is characterized by asymmetry associated with an extensor synergy pattern of hip extension and adduction, knee extension, and ankle plantar flexion and inversion. There are characteristic changes in the spatiotemporal, kinematic and kinetic parameters, and dynamic electromyography patterns.

There is still no consensus among different specialists on the subject of kinematic variation during the hemiparetic gait; one of the most frequently discussed joints is the knee, including the main changes that take place during the gait cycle and whether the gait velocity changes the patterns of joint mobility. [6]

Spatiotemporal parameters of gait refer to walking velocity, step length, stride length, and cadence; these are typically all decreased in hemiparetic walking. Walking velocity is often decreased to maintain an appropriate rate of energy expenditure.

Gait asymmetry may be evident in the changes in stance and swing phase durations and single and double support durations. Stance duration and single support duration are both decreased in the affected side whereas swing duration is increased. Stance duration and double-support time are both increased in non-affected side.

Table 1presents the effect of hemiparesis on spatiotemporal gait parameters.

Effect of hemiparesis on spatiotemporal gait parameters	
Walking velocity (m/s)	Decreased
Stride length (m)	Decreased
Step length (m)	Decreased
Cadence (steps/min)	Decreased
Paretic single-stance duration (s)	Decreased
Double-stance duration (s)	Increased
Paretic stance duration (s)	Decreased
Paretic swing duration (s)	Increased

Table 1: Effect of hemiparesis on spatiotemporal gait parameters. [6]

Gait kinematics refer to joint angles, velocities, and accelerations during gait. There are characteristic kinematic changes, which may be observable clinically. Table 2 Effect of hemiparesis on kinematic gait parametersTable 2 shows the main kinematic changes observed in the hemiparetic gait.

Effect of hemiparesis on kinematic gait parameters	
Pelvis	
Tilt	Increased
Hip	
Flexion at heel Strike	Decrease
Flexion at midswing	Decrease
Extension at preswing	Decrease
Knee	
Flexion at heel strike	Decrease
Flexion in swing	Decrease
Extension in stance	Increase
Ankle	
Dorsiflexion at heel strike	Decrease
Plantar flexion in swing	Increase
Inversion in swing	Increase

Table 2 Effect of hemiparesis on kinematic gait parameters. [6]

2.3 Gait Symmetry

Symmetry is defined as the correspondence of body parts in size, shape, and relative position, on opposite sides of a dividing line or distributed around a central point or axis. Asymmetry on the other hand, is simply defined as the absence of symmetry. [7]

Gait symmetry is considered present when equal values, or no statistical differences, of gait variables exist on both sides of the body. (Griffin, 1995)

For many rehabilitation professionals a goal of gait re-education is the achievement of symmetry of the body. The symmetry is an important gait feature that is measured and reported frequently, particularly in patients with hemiparesis. Symmetry calculations based on different spatiotemporal gait parameters can offer information about the control of walking. In addition, gait symmetry is important clinically since it may be associated with a number of negative consequences such as inefficiency, challenges to balance control, risk of musculoskeletal injury to the non-affected lower limb and loss of bone mass density in the paretic lower limb.(Patterson, 2010)

The most common parameters used to evaluate the symmetry are the step length, the swing time and the stance time.

According to the literature (Sadeghi 2000), [11], (Patterson 2008) there are different methods to compute the symmetry, some them are: index, ratio, absolute difference between the right and left side and statistical methods Figure 12.

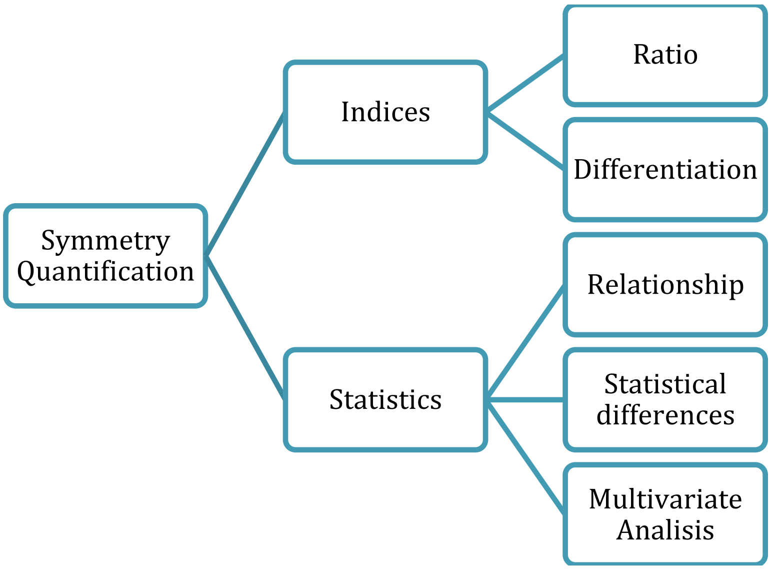


Figure 12: Quantification of symmetry. [10]

Symmetry index: computes the degree of symmetric behavior by calculating the difference between affected side and non-affected side for a given parameter and dividing the result by the bilateral average. Index values close to zero indicate symmetric behavior. (Sadeghi 2000)

$$Symmetry\ index(SI): SI = \left[\frac{\left(V_{affected\ side} - V_{non\ affected\ side}\right)}{0.5 * \left(V_{affected\ side} + V_{non\ affected\ side}\right)}\right] * 100$$

Where V is a spatiotemporal parameter (step length, swing time or stance time).

Ratio: computes the difference between a parameter of non-affected side and the same parameter of the affected side divided by the associated values at the non-affected side:

$$R = \left[\frac{V_{non\ affected\ side} - V_{affected\ side}}{V_{non\ affected\ side}}\right] * 100$$

When this ratio is close to zero it means that exist symmetry in the gait pattern analyzed. As the value moves away from zero, asymmetry increases. It will be negative when the parameter measured in the affected side is higher than the same parameter measure in the non-affected side. It will be positive when the parameter measured in the affected side is lower.

Using statistical approaches could provide better insight into understanding a complex phenomenon such as gait asymmetry. This is because many factors are involved, including a large number of gait parameters that should be evaluated at the same time, e.g. laterality, disability, functional behavior of the lower limbs, compensatory mechanisms, etc. There are statistical tools that allows to evaluate several gait parameters in a single analysis. Some studies have included correlation coefficients,

coefficients of variation, variance ratios, multivariate analysis of variance (MANOVA). They also used a Pearson product-moment correlation to determine the relationships among different measured gait variables. Paired t-tests were also used between right and left limb data to determine the presence of gait asymmetry. (Sadeghi, 2000)

In the present work the calculation of the ratio (R) is used to reflect the value of the asymmetry.

3. Materials and methods

3.1 The biomechanics Laboratory

Gait analysis was acquired in the Biomechanics Laboratory of the Polytechnic University of Catalonia (UPC) using the OptiTrackTM system of NaturalPoint (Figure 13). This optical system includes 16 infrared cameras and a specific software which allows to calibrate the cameras and to acquire the markers positions on the three planes over time (marker trajectories). The model of the cameras is the V100:R2 that has a sample frequency of 100Hz, which is one measurement every 0.01 seconds.

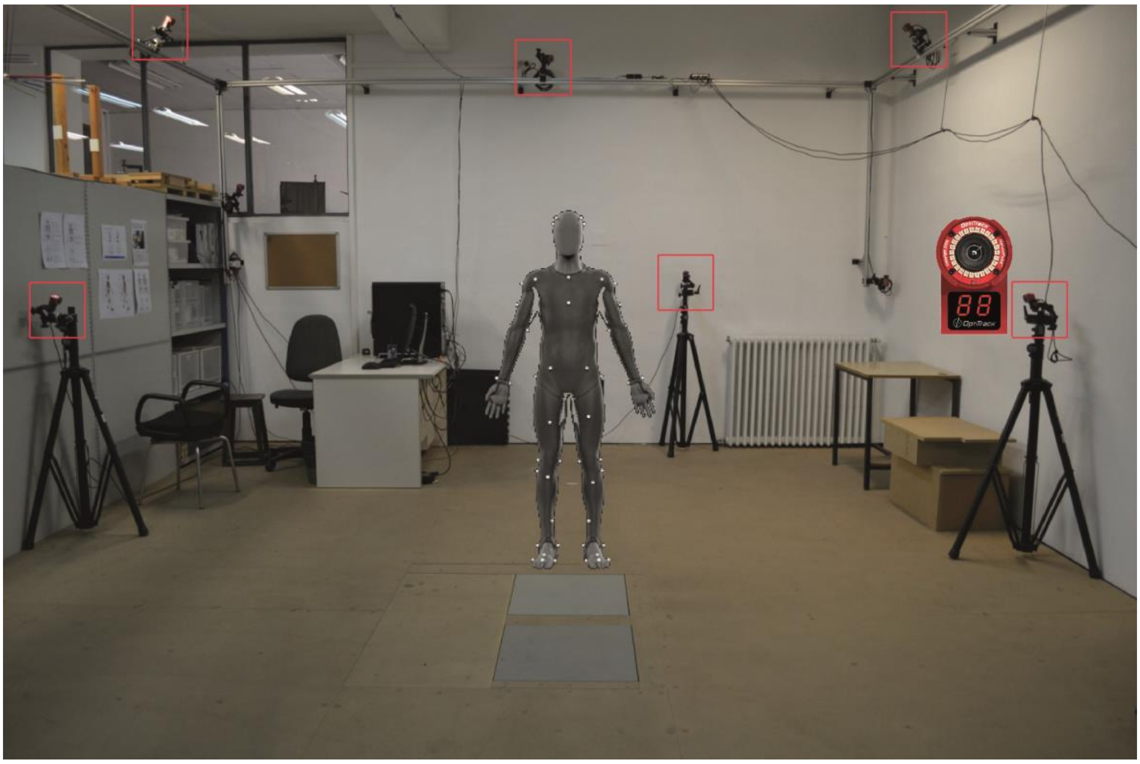


Figure 13: BIOMEC Lab in Universitat Politècnica de Catalunya.

Markers are small spheres covered by a reflector tissue, and reflect the infrared (IR) light emitted by the 26-LED ring surrounding the cameras. Figure 14 shows a passive reflective marker and a camera.

The signals from the cameras are transferred to a computer through the hubs, which are USB connection boxes where up to six cameras can be connected with USB 2.0

cables. These signals are processed with the software Motive, which allows not only the capture of the movement, but also the treatment of the captured data, as well as its export.

Figure 14. Camera IR and marker.

3.1.1 Calibration

The camera system needs to be calibrated, which involves both dynamic and static calibration. The dynamic calibration is performed with a wand-like tool (Figure 15), which has three markers on the end. This tool has to move around of the work volume. Using the coincidental points and relative distances of the three markers and by capturing them, the intrinsic and extrinsic parameters of the camera system are calculated. The intrinsic parameters describe the variables that depend on the camera optics, whereas the extrinsic ones describe the spatial pose of the camera.

Is important to make sure that all the cameras are able to draw the trajectory made with the wand. The software have a calibrate panel where shows the image captured for each camera and it evaluate the quality of the calibration.

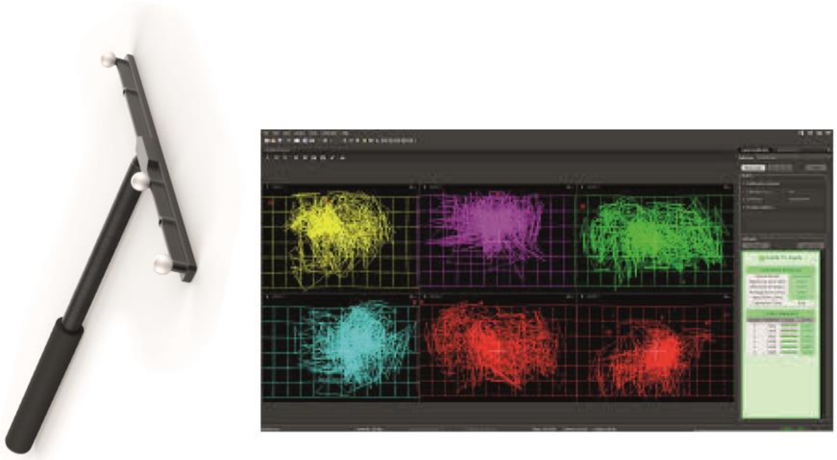


Figure 15. Dynamic calibration tool and panel calibration of software.

The static calibration determines the position and orientation of the camera with respect to the global coordinate system. The An L-shaped plate equipped with three markers set at a pre-defined distanced is placed on the floor at the center of the volume that the motion captures takes place. Figure 16

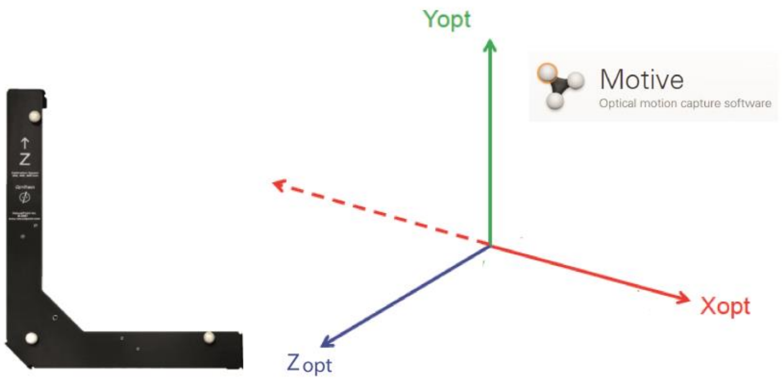


Figure 16: Static calibration tool and system reference.

3.2 Walking o'clock Device

The walking o'clock device is an electronic device with an inertial measurement unit (IMU) of nine axes (triple-axis accelerometers, gyroscopes and magnetometers). It works using quaternions to define the orientation of rigid bodies in three-dimensional space. It can record up to 200 measurements per second.

The device uses an auditory feedback to correct and to guide motor performance during the gait. It is placed on both tights of the patients with a velcro strap and it measures the angle of the thigh with respect to the vertical axis in the sagittal plane.

When a person walks the trunk is aligned with the vertical axis, due to the angle measured by the device can be associate with the hip flexion.

First, the patient should be standing with both feet aligned and resting on the floor to calibrate the device on 0° in relation to the vertical line.

Next, the patient walks normally while the device records the angle values formed between the thigh segment and the vertical line. The device sends this data by wi-fi to the computer, where the therapist can see the maximum and the minimum value of the angle measured between the tight and the vertical line. The therapist checks the information and decides the appropriate angle to improve the patient's gait. The device will use this angle as threshold to produce the auditory feedback.

Figure 17: Walking O'clock device. [13]

The gait pattern is different form each patient, due to some patients need to increase the hip flexion angle and other patients need to decrease it. The device has two options called *Interval 1* and *Interval 2* that allow to choosing a feedback to increase or decrease the hip flexion. If the chosen angle is $θ_0$, the *Interval 1* is from 0° to $θ_0$ and Interval 2 is above $θ_0$ (Figure 18).

If the therapist wants to increase the flexion, he must use the *Interval 1*. This option produces a continuous auditory feedback to reach the threshold and the patient must keep flexing until the sound stops. On the other hand, if the therapist wants to decrease the angle, the feedback will be set on interval 2 and the patient must stop flexing when she/he hears the sound. In the extension case, the angles will be negative, but the methodology would be the same one.

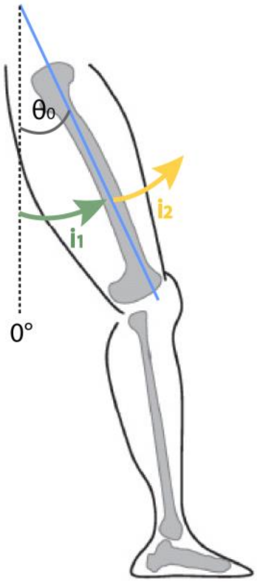


Figure 18: Reference angle ϑ_0 to explain the functioning of the feedback.

3.3 Biomechanical Model

The model used consists of 12 solids: torso, pelvis, femur (right and left), Tibia (right and left), talus, calcaneus, toes (right and left). It has 6 degrees of freedom with respect to the ground, 3 rotations and 3 translations. The other degrees of freedom of the model are the relative rotations between the different segments that constitute the model.

Each joint has a reference frame in the proximal and distal segments (for the hip joint, this is the pelvis and thigh; for the knee joint, the thigh and calf; for the ankle joint, the calf and foot). Joint angles are defined as a rotation of the distal segment relative to the proximal segment. The rotations are defined as follows:

Flexion and extension: take place about the medial/lateral axis of the proximal segment.

Internal and external rotation: take place about the longitudinal axis of the distal segment.

Abduction and adduction: take place about a floating axis that is at right angles to both the flexion/extension and internal/external rotation axes.

Table 3 and Figure 19 show a summary of model specifications.

The model used in the project is the Gait2392, provided by OpenSim. The model was created by Darryl Thelen (University of Wisconsin-Madison); and Ajay Seth, Frank C. Anderson and Scott L. Delp (Stanford University) (Delp, S. L., 2007). The metatarsal joint is not that relevant for our gait analysis and in this study it is blocked.

Joint	Proximal segment	Distal segment	DOF	Range of motions
Ground-Pelvis	Ground	Pelvis	6	Pelvis_tx Pelvis Tilt Pelvis_ty Pelvis List Pelvis_tz Pelvis Rotation
Hip	Pelvis	Thigh	3	Hip_flexion Hip_adduction Hip_rotation
Knee	Thigh	Calf	1	Knee_flexion
Ankle	Calf	Foot	1	Ankle flexion

Table 3: Model specifications

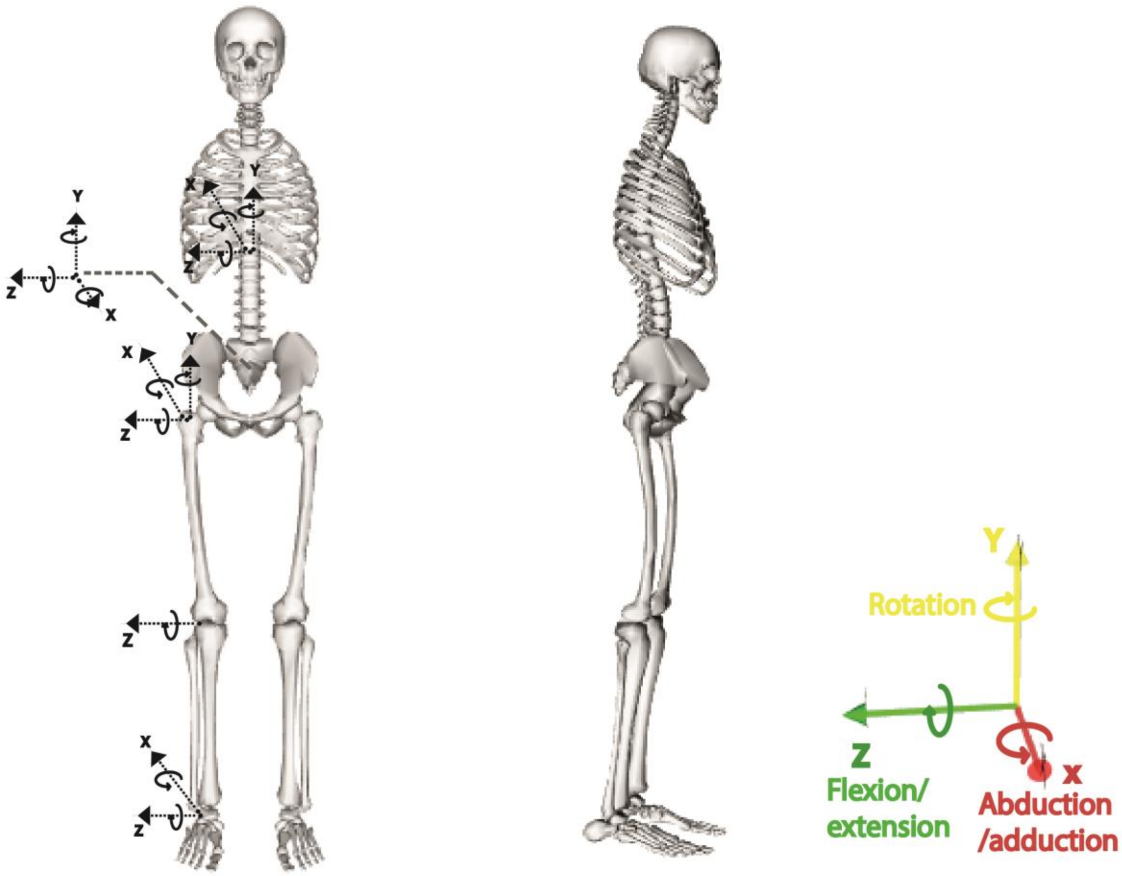


Figure 19: Skeletal model showing the joint angles. Frontal and lateral view.

3.4 Marker protocol

Body landmarks are points easy to find and close to the bones. So, these points do not have mobility associated to soft tissues, or it is much reduced.

Three markers per segment are normally used in order to minimize the errors of the motion capture. The position of the markers on the body and the distribution of the cameras must ensure that each marker is detected by at least 2 cameras at the same time.

The marker protocol used for all the captures is based on the Plug-in-Gait marker placement for lower limbs. Moreover the head and the trunk are included according to OpenSim model Gait 2392 markers.

The protocol then includes 24 markers, which are distributed and grouped as shown in Figure 20 with the names used in the OpenSim software.

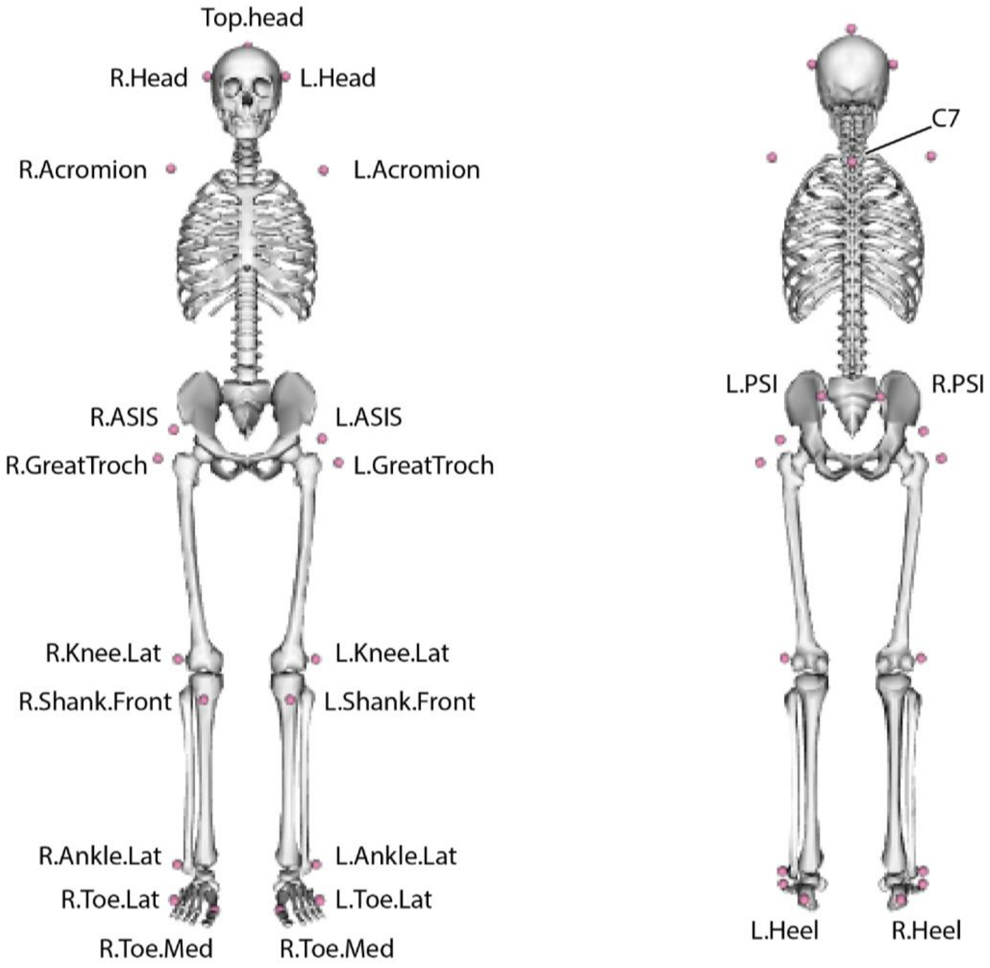


Figure 20: Distribution of the markers in the body. Frontal and back view. [14]

3.5 Subject

The study was carried out with four pediatric patients with hemiparesis. The patients have been selected by San Joan de Déu Hospital rehabilitation therapists and they have been referred to the BIOMEC lab. The patients 'age range from 9 to 17 years, one male and three female. Three patients uses an Ankle-Foot Orthosis (AFO) in their affected leg (Figure 21). An AFO is a lower extremity braces that provide thin, flexible, external support to the foot, ankle and/or lower leg. Designed to help a patient maintain a functional position and it can improve stability.

Figure 21: AFO used by study participants.

3.6 Data Analysis

In order to determine if the implemented device produces changes in the symmetry of gait, an analysis of the spatiotemporal parameters and kinematic gait parameters was performed.

Eight spatiotemporal parameters (V), including cycle time, stance time, swing time, cadence, stride length, step length, step width and walking speed were measured and analyzed for each patient.

In addition, parameters related to gait kinematics, including displacements and angular velocity of the lower limbs, are analyzed. The range of angle are studied only in the sagittal plane for pelvis, hip, knee and ankle.

3.6.1 Placement of the markers

The markers must be placed in the same anatomical points of the OpenSim model, following the protocol that has been explained in the previous section 3.4.

The patients used their own shoes to perform the tests. The physiotherapist indicated that it was better to measure with footwear since it represents a more daily march. Moreover, they wore black shorts and shirt to prevent markers from clogging or reflections (Figure 22 and Figure 23).

Figure 22. Markers placed on patient 1 and patient 2.

Figure 23: Markers placed on patient 3 y patient 4.

3.6.2 Motion capture

A procedure was established to make the motion captures the same form in all the patients, which allows us to contrast the results.

Initially a static capture is performed during which the patient should be standing as still as possible in the center of the work area. The static capture is used to scale the model when using the OpenSim software and it allows us to check that all the markers are visible.

Four walking scenarios were collected:

1. Natural gait (N): The device is placed in both tights of the patients but audio feedback is not yet activated. The patient is asked to walk at comfortable speed. This test shows how the patient walks in their everyday life and it also allows the physiotherapist to evaluate how he should set the parameters of the device for the feedback. Table 4 shows the measures taken by the Walking O'Clock device in each patient.

2. Gait with feedback (F): The value of the feedback is selected by the physiotherapist in order to match the values of angles measured by the devices in both legs. The physiotherapist explains to the patient what to do when he hears feedback. The indications are different for each patient since each one needs a different strategy to reach the desired symmetry. Table 5 shows the feedback used with each patient.

3. Gait after feedback immediate (AFI): The patient is asked to train with feedback for 10 minutes. Then the feedback goes off and we measure the patient walking after having trained. This capture allows us to see if the patient put incorporated what was learned with the feedback in her/his gait.

4. Gait after feedback training (AFT): The patient rests for 5 minutes and we repeat the capture. This test intends to check if the patient incorporated the feedback after a period of time.

Patient	Affected side	Right measure		Left measure	
		Flexion [°]	Extension [°]	Flexion [°]	Extension [°]
1	Right	27.5	-9.2	34.09	-8.2
2	Right	36	-1	30	-1
3	Left	32.7	-3	23.9	-6.7
4	Right	29	-7.9	23.3	-5.3

Table 4: Measures taken by the Walking O'clock device.

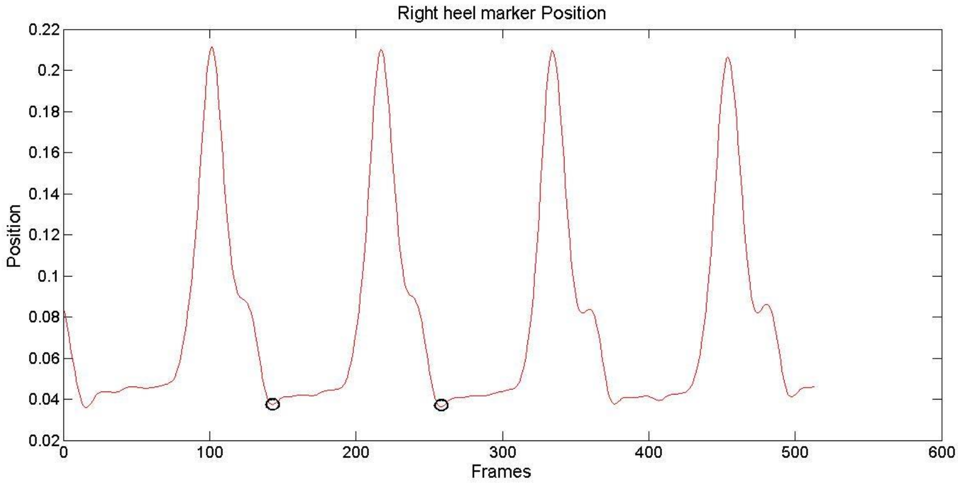
Patient	Affected side	Feedback set
1	Right	Flexion of 34° on right leg
2	Right	Flexion of 36° on left leg
3	Left	Flexion of 32° on left leg
4	Right	Extension of -7° on left leg

Table 5: Feedback used in each patient.

3.6.3 Symmetry calculation

The spatiotemporal parameters on both sides (affected and non-affected) were calculated and then used in the asymmetry calculate.

First, the Matlab software was used to detect 1 gait cycle in each analyzed capture. Three gait cycles were selected for each scenario, detecting two consecutive initial contact for each leg. These events were detected by finding the minimum heel positions on the Y axis. Figure 24



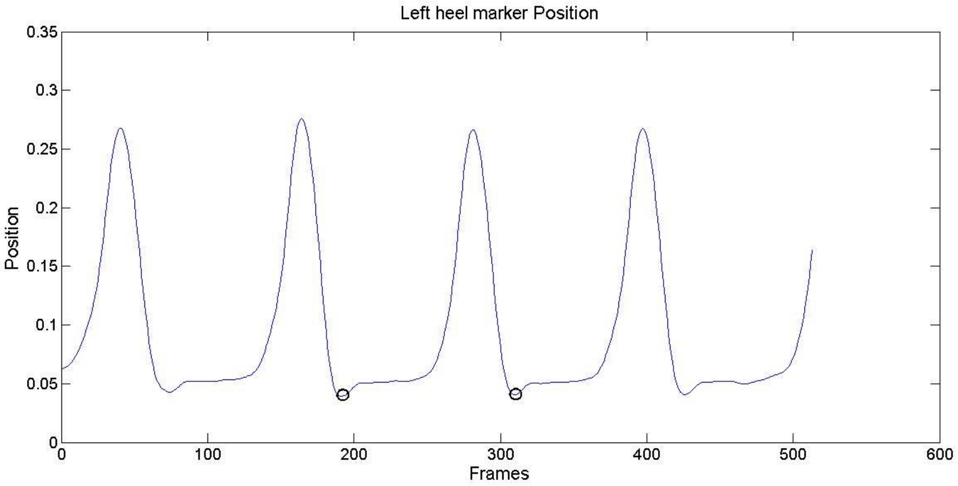


Figure 24: Trajectory on the Y axis of the right heel marker (red) and left heel marker (blue).

Once the cycles were detected (3 of each scenario), the spatiotemporal parameters were calculated and the mean and standard deviation of the 3 results were calculated. The results for each parameters in the 4 scenarios for each patient are in the annex 1.

As mentioned earlier, eight spatiotemporal parameters were calculated for each side (right and left side):

Cycle time: duration of the complete cycle from the first initial contact detected to the second initial contact. This measure is in miliseconds [mseg].

```
tcycle(i)=time(HS(2,i))-time(HS(1,i))
```

HS is a matrix that has saved the initial contacts of right and left heel strike for each captures (i).

Stance time: time from heel strike to toe-off in the same foot. This measure is in miliseconds [mseg].

```
tapoy(i)=time(TO(1,i))-time(HS(1,i))
```

Also, the stance phase was calculated as a function of the cycle time:

```
fapoy(i)=(time(TO(1,i))-time(HS(1,i)))*100/tcycle(i)
```

This measure is in percentage of the cycle [%]

Swing time: time from the first toe-off to the second heel strike of the same foot. This measure is in miliseconds [mseg].

```
tbal(i)=(time(HS(2,i))-time(TO(1,i)))
```

And swing phase in percentage of the cycle [%]:

```
fbal(i)=(time(HS(2,i))-time(TO(1,i)))*100/tcycle(i)
```

Cadence: is the number of steps taken in a minute.

```
cad_r(i)=60*2/tcycle(i)
```

Stride length: distance between the first heel strike and second heel strike. This measure is in meters [m].

```
lcycle(i)=xheel_r(HS(2,i))-xheel_r(HS(1,i));
```

Step length: for the right step is the distance between the second right heel strike and the first left heel strike. This measure is in meters [m].

```
lpaso_r(i)=xheel_r(HS(2,i))-xheel_l(HS(1,i));
```

Step width: the side to side distance between the lines of the two feet in the transverse plane. This measure is in meters [m].

```
Ancho(i)=abs(zheel_l(HS(3,i))-zheel_r(HS(1,i)));
```

Walking speed: the average speed is the product of the cadence and the stride length. The cadence, in steps per minute, corresponds to half-strides per 60 seconds or full strides per 120 seconds. This measure is in meters per seconds [m/s].

```
vel= lcycle*cad/120
```

Once the parameters for both sides were obtained, the asymmetry of each parameter is calculated using the ratio defined in section 2.3. The results tables are in the annex 1.

3.6.4 Joint Angles

For each of the scenarios (listed in section 3.6.2), three captures have been chosen. Therefore, twelve captures per patient have been processed and one static capture. The captures had to be edited before being exported from the Laboratory Software, Motive. In case a marker was missing or had been lost by the program during a period of frames in the capture, the gap was filled with the editing tool fill gaps.

The files then were exported as a .csv file extension. That file would be then transformed into a .trc file, which is the one that the software OpenSim reads. To do so, a Matlab program was created and used, which directly converted the files into .trc, just by executing them.

Joint angles were computed at each time instant in the model using the 'inverse kinematics' tool in OpenSim. The marker locations on the model were optimally matched to the trajectories of the corresponding marker locations measured on the subject, so that the sum of the squared error distances between the two marker sets was minimized, thereby yielding the optimal set of joint kinematics. To perform this process the scaling tool is used and then the inverse kinematics calculation.

The scaling of the model allows to create a skeleton model as close as possible to the real subject. In addition, it allows relocating the markers in the model in most similar way to how they were placed in reality. It is advisable to relocate them (Adjust Markers Model) once the model has already been adjusted and, therefore, the size is the appropriate one.

To perform the scaling it is necessary to define the scale factors, which are the relationship of the distance between two markers in reality and in the model. Once these factors are defined, they must be associated to the solids of the model. Figure 25 shows how this factors are defined:

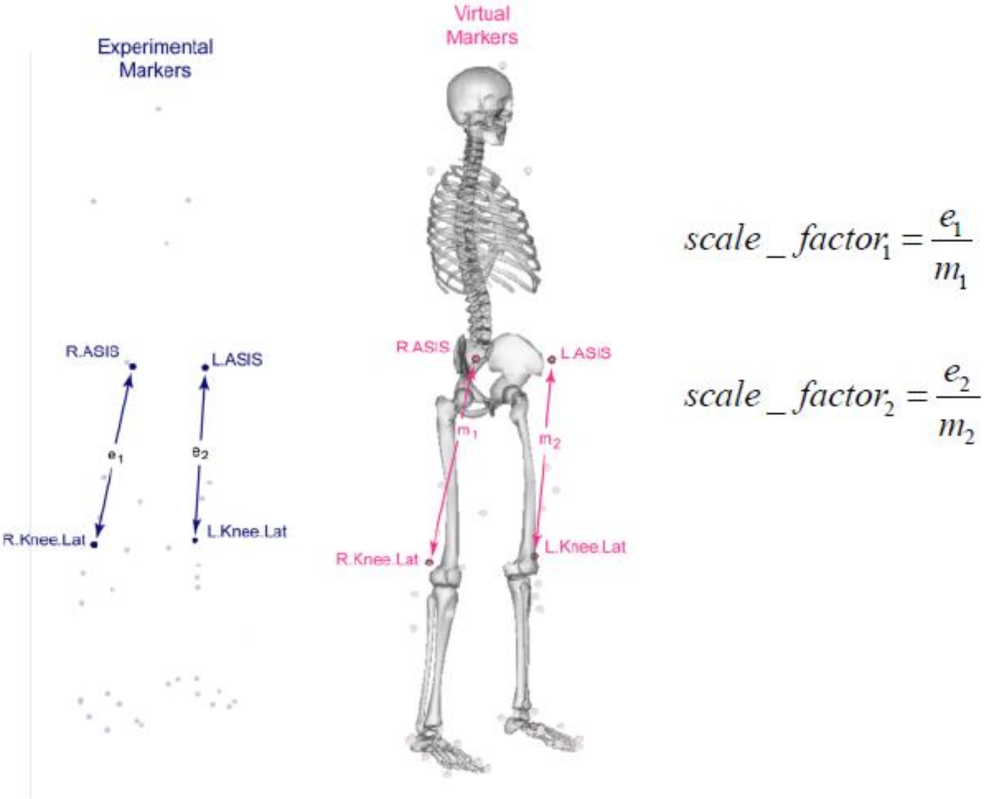
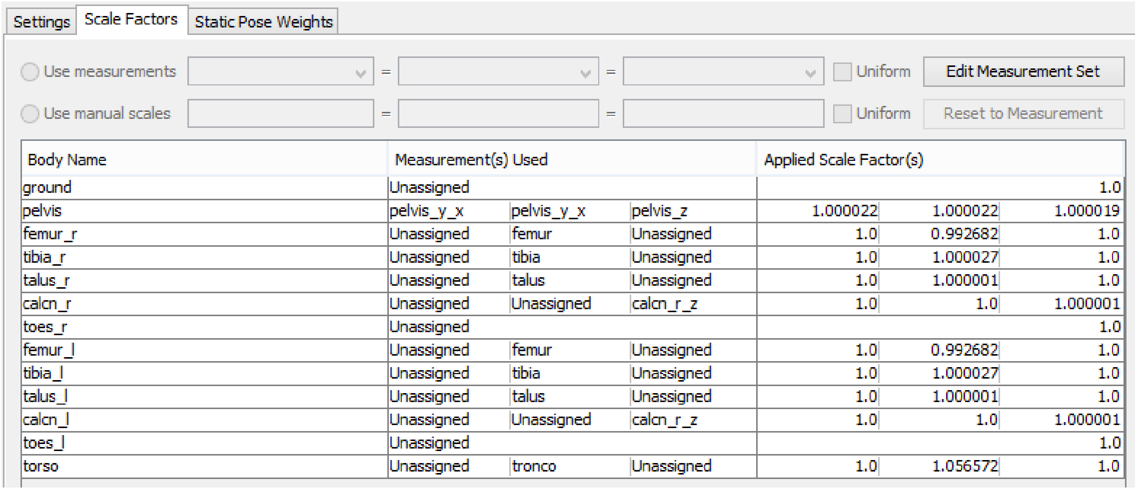


Figure 25: Scale tool. Distance between experimental and model markers.[14]

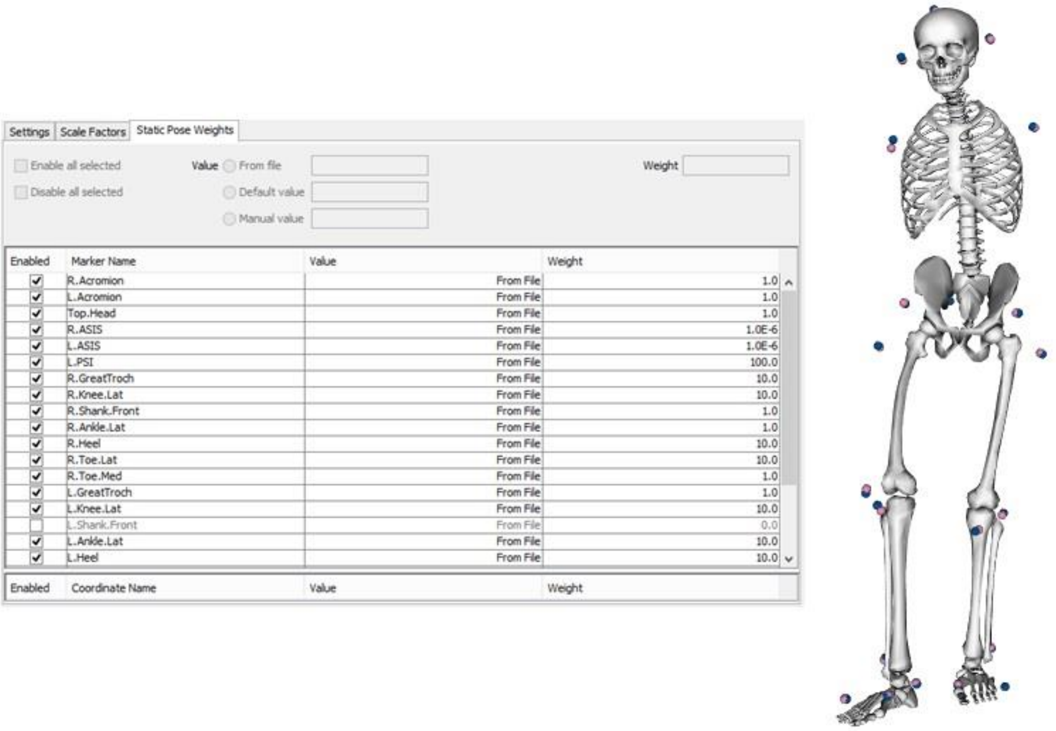


Body Name	Measurement(s) Used			Applied Scale Factor(s)		
ground	Unassigned					1.0
pelvis	pelvis_y_x	pelvis_y_x	pelvis_z	1.000022	1.000022	1.000019
femur_r	Unassigned	femur	Unassigned	1.0	0.992682	1.0
tibia_r	Unassigned	tibia	Unassigned	1.0	1.000027	1.0
talus_r	Unassigned	talus	Unassigned	1.0	1.000001	1.0
calcn_r	Unassigned	Unassigned	calcn_r_z	1.0	1.0	1.000001
toes_r	Unassigned					1.0
femur_l	Unassigned	femur	Unassigned	1.0	0.992682	1.0
tibia_l	Unassigned	tibia	Unassigned	1.0	1.000027	1.0
talus_l	Unassigned	talus	Unassigned	1.0	1.000001	1.0
calcn_l	Unassigned	Unassigned	calcn_r_z	1.0	1.0	1.000001
toes_l	Unassigned					1.0
torso	Unassigned	tronco	Unassigned	1.0	1.056572	1.0

Figure 26: Scale factor for each body and the measurements used.

After the skeletal model scale is done, the option *Adjust Model Markers* follows, to relocate the markers as similar to where they were in reality as possible from a .trc file.

In the *Static Pose Weights*, it is desirable to set different weights on the markers, since this is the weight that each marker will have in the optimization carried to adjust its position. Low weight markers are those with less precise positions. On the other hand, high weight markers are those with a precise anatomic location.



Enabled	Marker Name	Value	Weight
☑	R.Acromion	From File	1.0
☑	L.Acromion	From File	1.0
☑	Top.Head	From File	1.0
☑	R.ASIS	From File	1.0E-6
☑	L.ASIS	From File	1.0E-6
☑	L.PSI	From File	100.0
☑	R.GreatTroch	From File	10.0
☑	R.Knee.Lat	From File	10.0
☑	R.Shank.Front	From File	1.0
☑	R.Ankle.Lat	From File	1.0
☑	R.Heel	From File	10.0
☑	R.Toe.Lat	From File	10.0
☑	R.Toe.Med	From File	1.0
☑	L.GreatTroch	From File	1.0
☑	L.Knee.Lat	From File	10.0
☐	L.Shank.Front	From File	0.0
☑	L.Ankle.Lat	From File	10.0
☑	L.Heel	From File	10.0

Enabled	Coordinate Name	Value	Weight

Figure 27: Static pose weights used and model scaled and adjusted.

The kinematics of the system bodies can be obtained through inverse kinematics. The resulting file is a *Motion* file (.mot extension), which contains the value of the generalized coordinates of the model in every instant of the capture.

4. Results

This chapter presents the results obtained from the motion capture, and an analysis of these data. For each patient, this section show:

1. A bar chart containing the spatiotemporal asymmetry values.
   This data is calculated from the individual spatiotemporal parameters obtained for each lower limb (see Annex 1), according to the methodology explained in section 2.3.

2. An analysis of the angular coordinates in the sagittal plane.
   This coordinates are:
   - Pelvic tilt angle
   - Right and left knee flexion angles
   - Right and left hip flexion angles

- Right and left ankle flexion angles

Related to these angular variables, the following results can be seen:
Plots:

- Figures containing four plots (one for each test, i.e., N, F, AFI and AFT) are used to analyse the performance of one joint coordinate at each scenario. Therefore, for each patient, three of these figures are presented (containing hip, knee and ankle coordinates respectively). The plots contain the evolution of one angular coordinates, and right and left angles are plotted together in order to facilitate the comparison between the affected and non-affected leg. This procedure was performed using software OpenSim and software Matlab with the methodology explained in section 3.6.4.

- The Root Mean Square Error (RMSE) along the cycle is used in order to quantify the angular variables differences between non-affected and effected side. The obtained results are plotted in the corresponded graph.

- Vertical lines represent the end of the stance phase and the beginning of the swing phase. There are two lines, one line for each leg.

Tables:

- The range of motion (RoM) of each coordinate is calculated at each scenario. This is the measurement of the movement around a specific joint. It is calculated by the difference between the maximum and minimum joint angle.

- The Root Mean Square Error (RMSE) between angular velocity of non-affected side and angular velocity of affected side during the whole cycle.

The following section shows the results obtained for each patient.

4.1.1 Patient 1

Patient 1 was put under a feedback right thigh angle of 34°. The goal of the set feedback is for the patient to achieve greater right hip flexion by trying to match the one of the left leg. The physiotherapist explained to the patient that he should raise his right leg more when he hears feedback.

Figure 28 shows the asymmetry calculated for different spatiotemporal parameters. It is observed that the parameters with greater asymmetry in the Natural stage are: stance time, swing time, step length and step width.

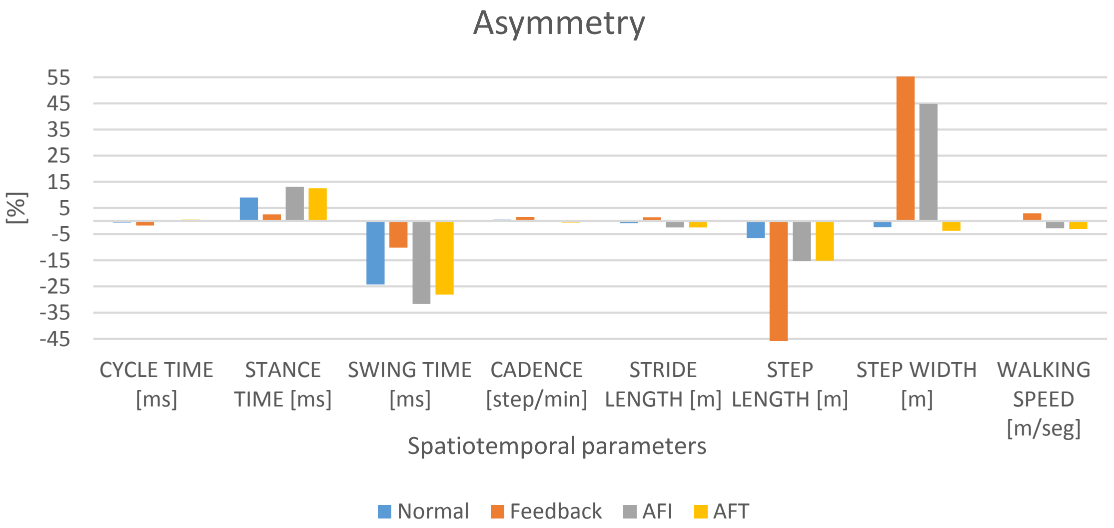


Figure 28: Asymmetry calculated with different temporal-spatial gait parameters for the four scenarios of Patient 1.

If we look at the parameter of support time it seems that the asymmetry has decreased, this meaning that the support times of the affected and unaffected side are more symmetrical. What really happens in this case is that the time of support on the unaffected side has decreased, approaching to the value of the affected side. This effect is related to the interpretation of the feedback that the patient performed. When the patient 1 listened the feedback, he lowered the affected leg quickly, reducing the time of support in the unaffected leg. With respect to this parameter, the feedback manages to reduce the asymmetry. However, this case the symmetry is obtained by changing the stance time of the non-affected side, which becomes similar to that of the affected side. The numerical data is in Annex 1.

Regarding the parameters of swing time, it occurs the same problem. The step length and step width also have no improvements. It is thought that patient 1 could not understand what he had to do with the feedback.

Figure 29 shows the hip flexion angle pattern measured in the affected side and non-affected side for the different scenarios of the Patient 1. There was no improvement in the tendency between the two curves and the RMSE value gets higher in each stage.

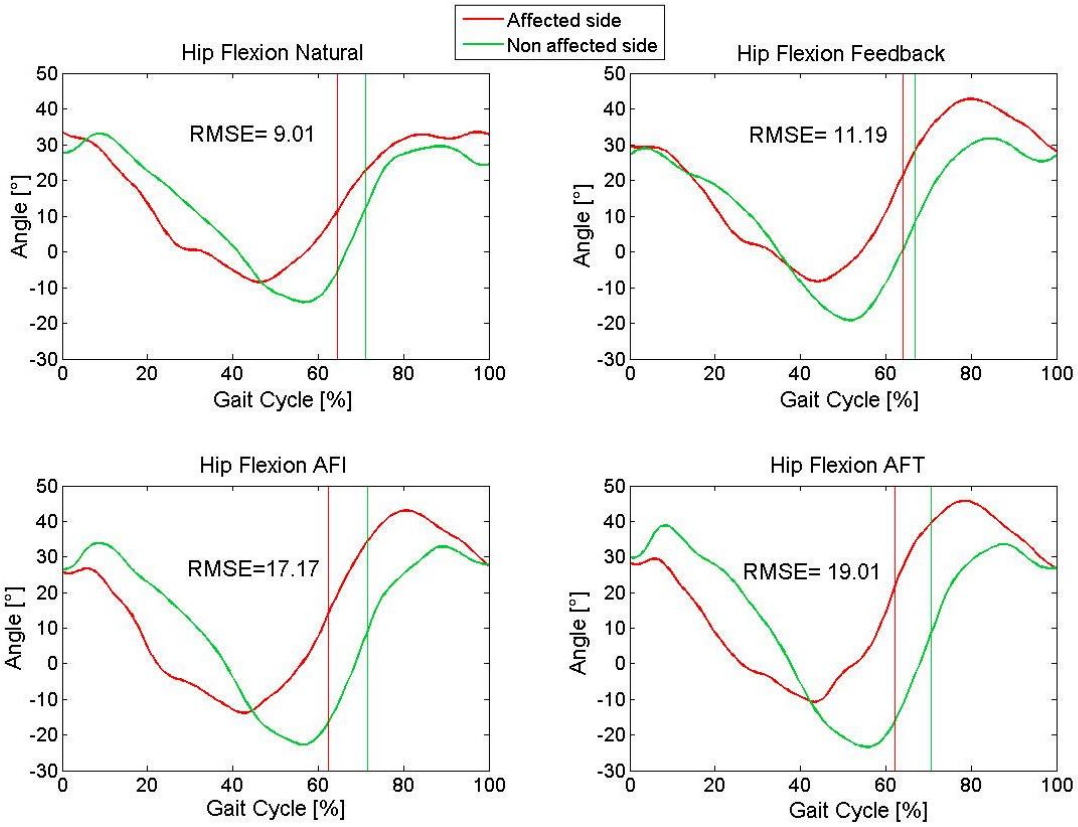


Figure 29: Hip flexion angle in affected and non-affected side measured for the four scenarios. RMSE in degrees.

Figure 30 shows the knee flexion angles in the four scenarios and it can be seen that the RMSE in the feedback scenario is lower than the RMSE in the natural scenario. This represents an improvement in the symmetry of knee rotations. However, the RMSE in AFI stage and AFT stage are higher than RMSE in natural stage.

Figure 31 shows the ankle dorsiflexion angles in the four scenarios. In this joint the RMSE is reduced in the feedback scenario but then it increases.

If the natural scenario is compared with the AFT scenario, Patient 1 has not had improvements in the asymmetries of the articular angles.

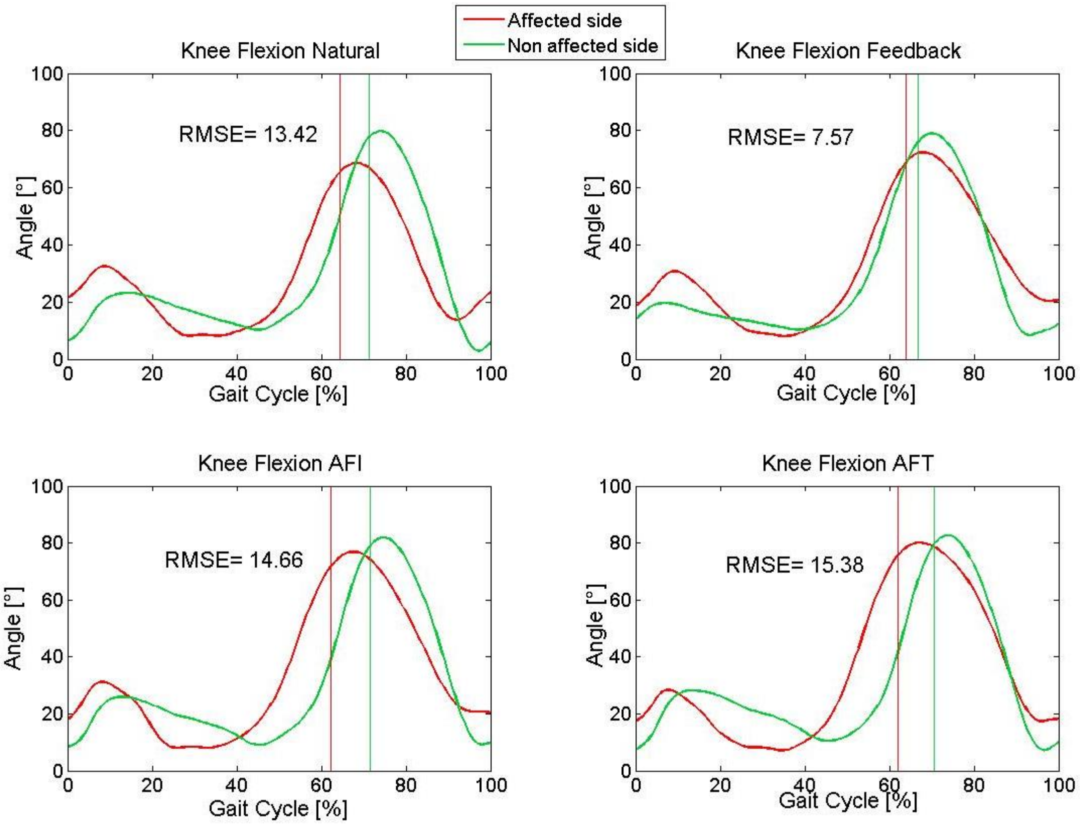


Figure 30: Knee flexion angle in affected and non-affected side measured for the four scenario. RMSE in degrees.

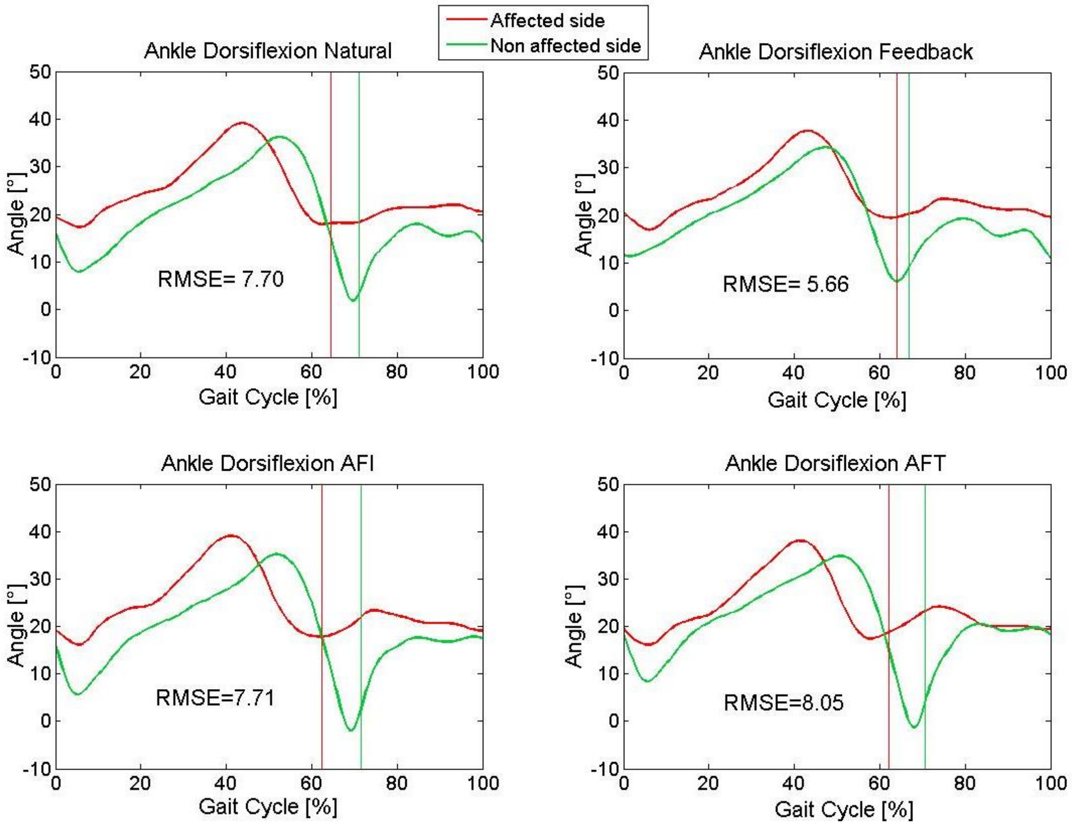


Figure 31: Ankle dorsiflexion angle in affected and non-affected side. RMSE in degrees.

Table 6 shows maximum and minimum peaks and range of motion of the estimated angles for the four scenarios of Patient 1. It is observed that the values in the pelvis are negative in flexion, which indicate that the patient has anterior pelvis tilt.

With respect to the hip, it is observed that the symmetry has not increased but the RoM in the affected side has increased in the different scenarios.

Regarding the knee, it is observed that the RoM has increased in the different scenarios. With respect to the ankle, small increases are seen in the RoM of the affected side.

Patient 1		Natural		Feedback		AFI		AFT	
		Value [°]	RoM [°]	Value [°]	RoM [°]	Value [°]	RoM [°]	Value [°]	RoM [°]
Pelvis									
	Flexion	0.26	7.38	3.71	12.53	4.81	10.37	4.89	14.52
	Extension	-7.12		-8.82		-5.56		-9.63	
Hip									
Affected side	Flexion	33.48	42.01	42.73	51.08	42.97	56.83	45.72	56.51
	Extension	-8.52		-8.36		-13.86		-10.79	
Non-affected side	Flexion	33.08	47.19	31.68	50.91	33.88	56.62	38.80	62.22
	Extension	-14.11		-19.23		-22.75		-23.43	
Knee									
Affected side	Flexion	68.55	60.35	72.29	64.22	76.82	68.79	80.05	72.95
	Extension	8.20		8.08		8.03		7.10	
Non-affected side	Flexion	79.76	76.90	78.89	70.47	81.92	73.57	82.65	75.45
	Extension	2.86		8.42		8.35		7.19	
Ankle									
Affected side	Dorsi flexion	39.14	21.86	37.72	20.80	39.03	22.92	38.02	21.92
	Plantar flexion	17.28		16.91		16.11		16.10	
Non-affected side	Dorsi flexion	36.18	34.32	34.26	28.17	35.18	37.16	34.79	36.07
	Plantar flexion	1.86		6.09		-1.98		-1.28	

Table 6: Peak and range of motion angular kinematics for the four test of Patient 1.

Table 7 shows the RMSE between angular velocity of non-affected side and angular velocity of affected side. It is observed that the RMSE has decreased between natural and feedback scenarios for hip, knee and ankle but it is not maintained in the other scenarios (AFI and AFT).

RMSE Angular velocity [°/s]	Natural	Feedback	AFI	AFT
Hip	44.0	38.6	62.1	67.8
Knee	96.2	53.9	97.9	95.7
Ankle	60.5	37.6	67.7	73.6

Table 7: RMSE between angular velocity of non-affected side and angular velocity of affected side of Patient 1.

4.1.2 Patient 2

Figure 32 shows that Patient 2 has increased the symmetry of six parameters: cycle time, stance time, swing time, cadence, step width and walking speed. However, it has deteriorated the asymmetry of two parameters: stride length and step length. The improvement in the symmetry of the step width is noticeable.

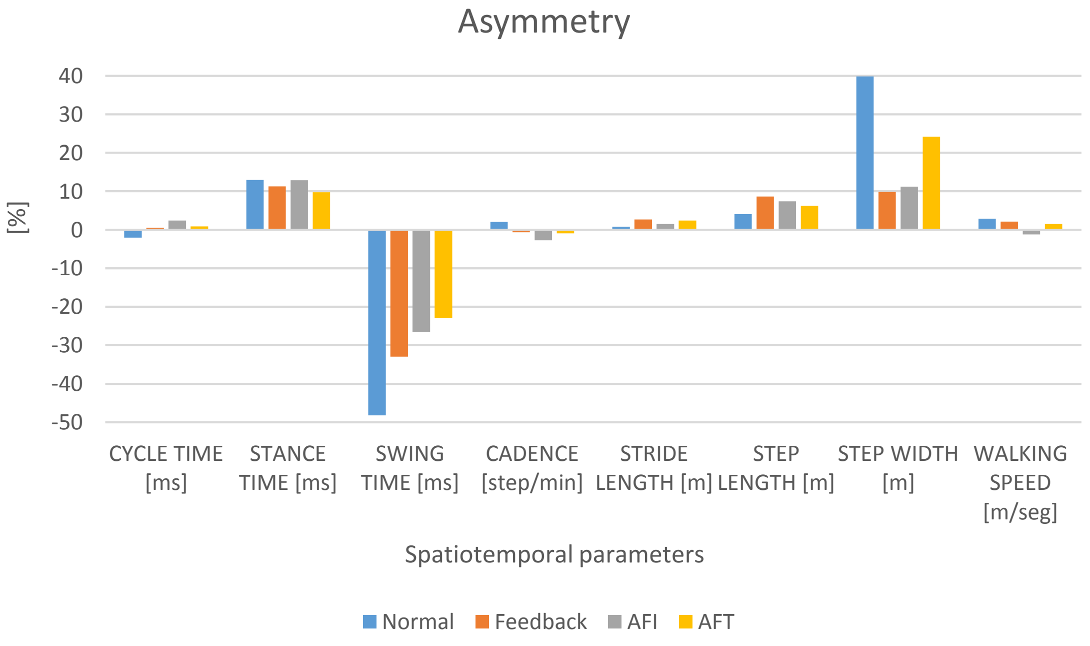


Figure 32: Asymmetry calculated with different temporal-spatial gait parameters for the four scenarios of Patient 2.

Figure 33 shows that the symmetry of hip flexion angles has increased in the stance phase but it is worse during the swing phase. The RMSE increases in the different scenarios due to the difference in the swing phase. In the knee flexion angles occurs the same: the symmetry improves in the stance phase but gets worse in the swing phase (Figure 34).

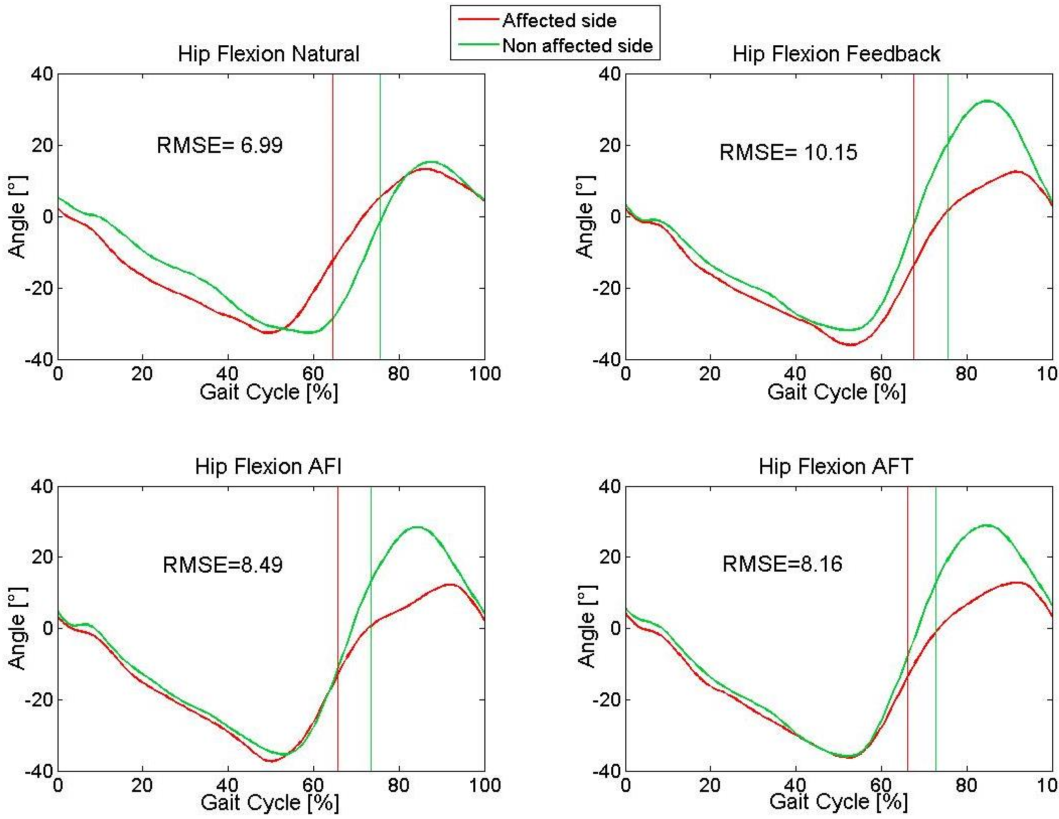


Figure 33: Hip flexion angle in affected and non-affected side measured for the four scenarios. RMSE in degrees.

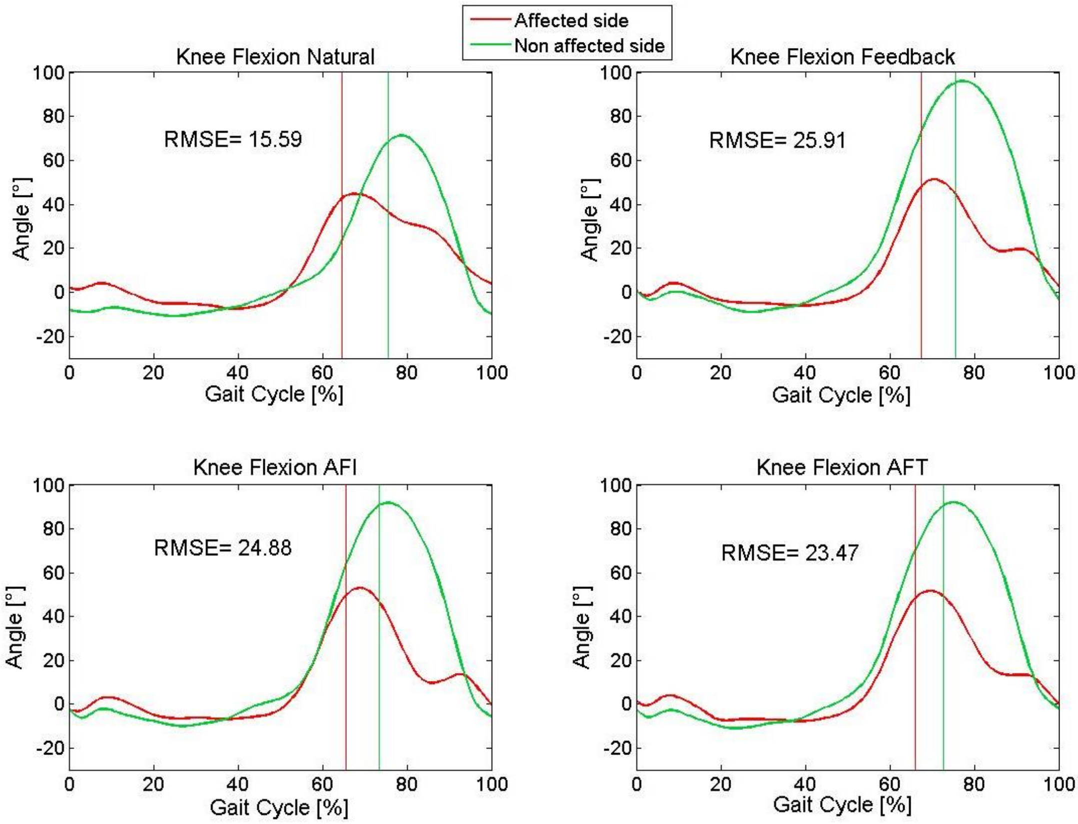


Figure 34: Knee flexion angle in affected and non-affected side measured for the four scenarios. RMSE in degrees.

Figure 35 shows that the ankle dorsiflexion angles have not increased their symmetry but they have a similar tendency in feedback, AFI and AFT scenarios. It has been observed that the asymmetry is higher during the swing phase.

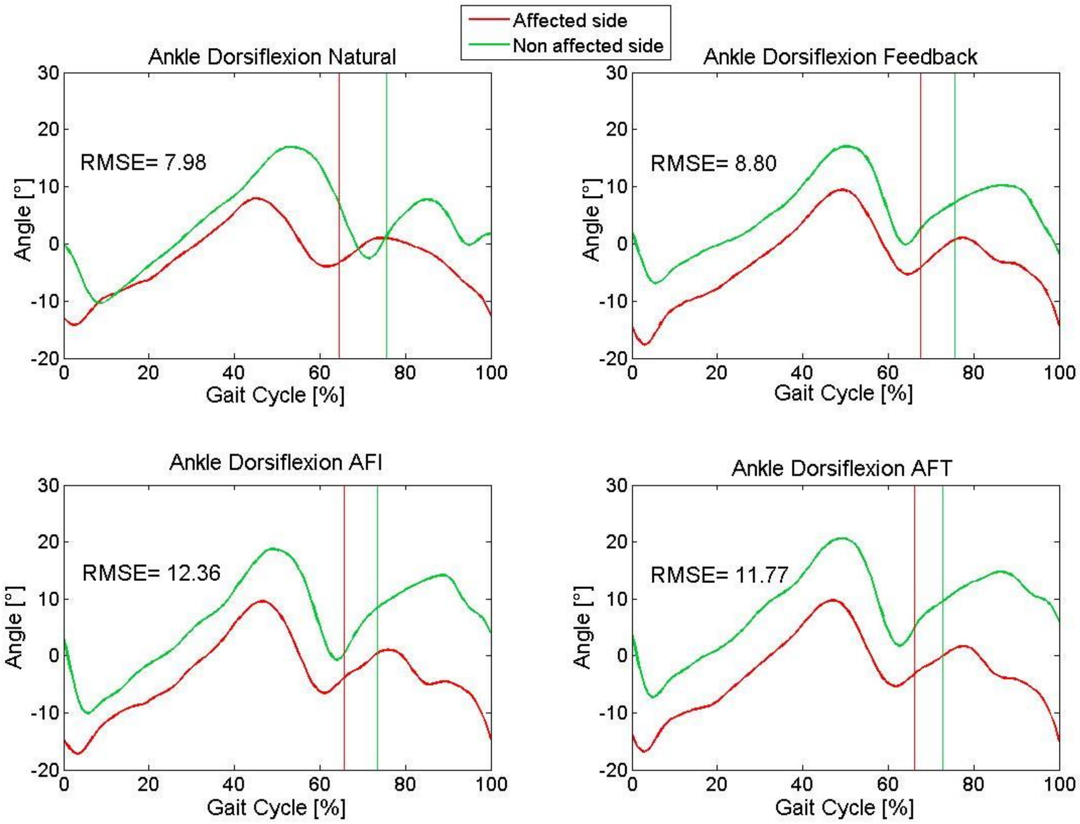


Figure 35: Ankle dorsiflexion angle in affected and non-affected side. RMSE in degrees.

Table 8 shows the peaks and RoM measured for the patient 3. It has observed that the RoM of hip, knee and ankle have increased in the affected side. The patient wears an ankle foot orthosis (AFO) in the affected side and therefore to the RoM of the affected ankle is limited.

Table 9 shows that the RMSE of the angular velocity has decreased between the natural and AFT scenarios in hip, knee and ankle. This means that the patient has increased the control of the affected limb joint.

Patient 2		Natural		Feedback		AFI		AFT	
		Value [°]	RoM [°]	Value [°]	RoM [°]	Value [°]	RoM [°]	Value [°]	RoM [°]
Pelvis									
	Flexion	16.75	7.63	18.38	5.84	17.11	4.46	16.43	4.82
	Extension	9.13		12.54		12.65		11.62	
Hip									
Affected side	Flexion	13.20	45.88	12.40	48.46	12.25	49.57	12.86	49.14
	Extension	-32.67		-36.07		-37.32		-36.28	
Non-affected side	Flexion	15.20	47.81	32.19	64.12	28.36	63.78	28.83	64.75
	Extension	-32.61		-31.93		-35.42		-35.92	
Knee									
Affected side	Flexion	44.67	52.29	51.30	57.49	52.98	60.00	51.59	59.45
	Extension	-7.62		-6.19		-7.01		-7.87	
Non-affected side	Flexion	71.21	82.11	95.93	105.08	91.82	101.91	91.99	103.10
	Extension	-10.90		-9.15		-10.09		-11.12	
Ankle									
Affected side	Dorsi flexion	7.93	22.13	9.43	27.08	9.55	26.76	9.72	26.58
	Plantar flexion	-14.21		-17.65		-17.21		-16.86	
Non-affected side	Dorsi flexion	16.97	27.37	17.00	23.90	18.72	28.79	20.61	27.93
	Plantar flexion	-10.40		-6.90		-10.06		-7.32	

Table 8: Peak and range of motion angular kinematics for the four test of Patient 2.

RMSE Angular velocity [°/s]	Natural	Feedback	AFI	AFT
Hip	36.2	38.2	36.7	32.5
Knee	111.8	117.9	124.3	109.7
Ankle	52.2	26.3	35.4	34.2

Table 9: RMSE between angular velocity of non-affected side and angular velocity of affected side of Patient 2.

4.1.3 Patient 3

The patient 3 did not complete the last scenario (AFT) because she was very tired. Figure 36 shows that the stance time, swing time and step width were the parameters with greater asymmetry in the natural scenario. It is observed that the asymmetry related with the stance time has decrease in the feedback scenario but it has increased in the AFI scenario. The asymmetry related to swing time and step width has increased in the feedback and AFI scenario.

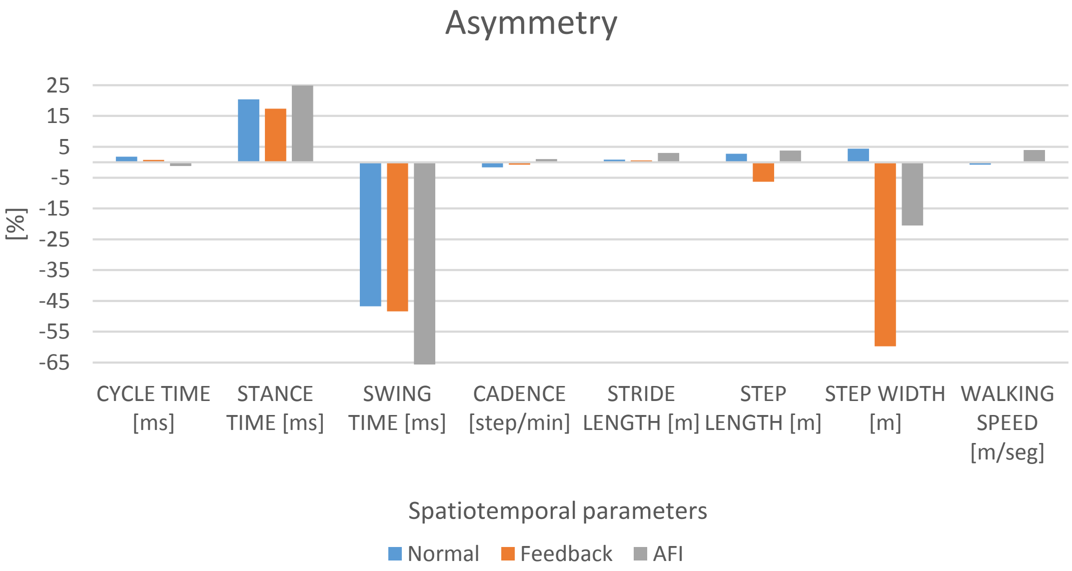


Figure 36: Asymmetry calculated with different spatiotemporal parameters for the four scenarios of Patient 3.

Figure 37 shows the hip flexion angles for patient 3. Although the RMSE increases in the different scenarios, there is a greater symmetry in the support phase for the feedback, AFI and ATF scenarios. In contrast, during the swing phase the asymmetry increases for the three scenarios.

Knee flexion presents the same behavior that hip flexion. For all the scenarios, the symmetry is better in stance phase but it gets worse during swing phase it is worse for the different scenarios (Figure 38).
Figure 39 shows the ankle dorsiflexion angles. The RMSE measured for the different scenarios increases but it is observed that the tendency of both side are similar, this is means that both ankle perform similar change in their angular movements.

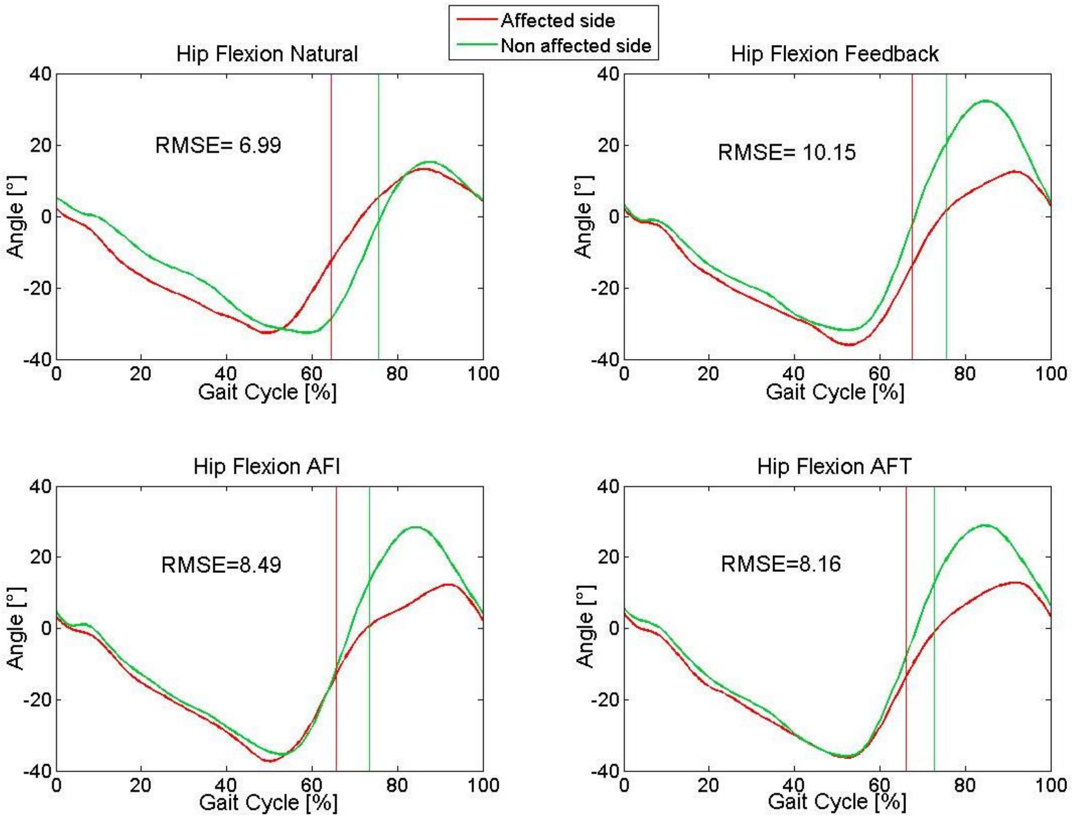


Figure 37: Hip flexion angle in affected and non-affected side measured for the four scenarios. RMSE in degrees.

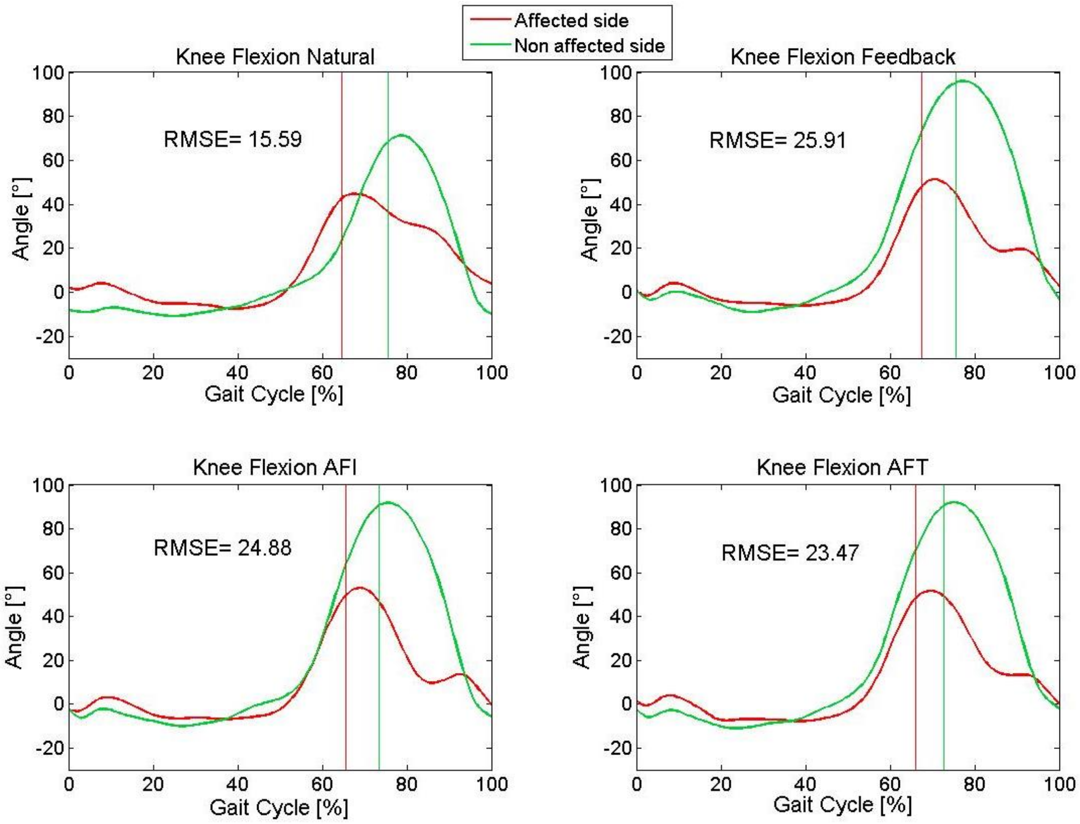


Figure 38: Knee flexion angle in affected and non-affected side measured for the four scenarios. RMSE in degrees.

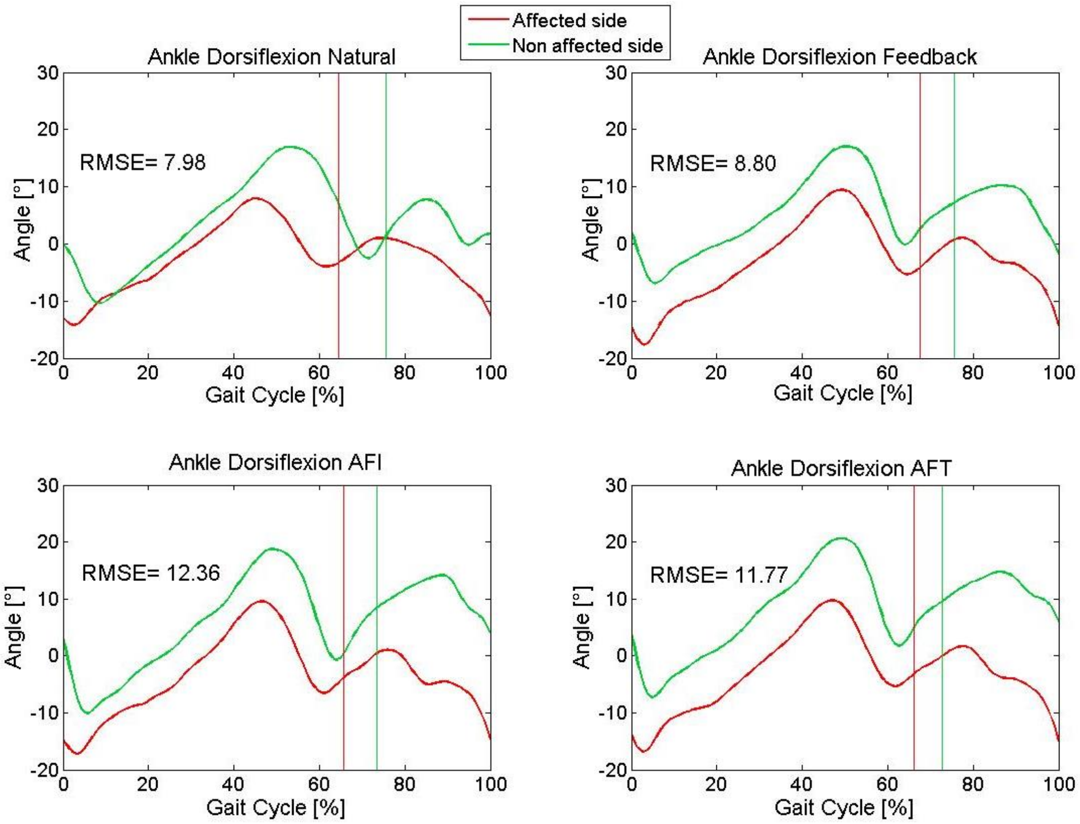


Figure 39: Ankle dorsiflexion angle in affected and non-affected side. RMSE in degrees.

Finally, Table 10 shows the peaks of flexion and extension angles and the RoM measured in patient 3. I can be seen that, for each scenario, the RoM is similar, only changes about 2 or 3 degrees are obteined.

It is observed that the slopes of the curves of the affected and unaffected side are different in the natural scenario for the three joints, and in the AFT scenario the slope of the affected side is similar to that of the unaffected side. This indicates that the patient has won stability in the hip, knee and ankle. This is also observed calculating the RMSE between angular velocities of the affected and non-affected side:
Table 11 shows that the RMSE decreased in feedback and after feedback scenarios.

Patient 3		Natural		Feedback		AFI	
		Value [°]	RoM [°]	Value [°]	RoM [°]	Value [°]	RoM [°]
Pelvis							
	Flexion	27.87	9.96	28.50	11.49	28.41	11.04
	Extension	17.91		17.01		17.37	
Hip							
Affected side	Flexion	27.79	59.18	28.60	57.94	26.77	56.57
	Extension	-31.40		-29.34		-29.80	
Non-affected side	Flexion	5.39	51.75	6.36	52.28	5.78	51.38
	Extension	-46.36		-45.92		-45.60	
Knee							
Affected side	Flexion	73.88	48.29	74.36	48.11	76.05	48.58
	Extension	25.58		26.25		27.47	
Non-affected side	Flexion	76.05	80.29	75.99	78.92	74.82	77.17
	Extension	-4.24		-2.93		-2.35	
Ankle							
Affected side	Dorsi flexion	35.43	46.33	37.30	41.81	36.86	44.56
	Plantar flexion	-10.90		-4.51		-7.70	
Non-affected side	Dorsi flexion	20.02	33.51	22.65	33.56	22.27	32.24
	Plantar flexion	-13.49		-10.90		-9.97	

Table 10: Peak and range of motion angular kinematics for the four test of Patient 3.

RMSE Angular velocity [°/s]	Natural	Feedback	AFI
Hip	75.26	76.26	42.05
Knee	115.86	115.02	60.71
Ankle	91.01	87.32	48.92

Table 11: RMSE between angular velocity of non-affected side and angular velocity of affected side of Patient 3.

4.1.4 Patient 4

Figure 40 shows the spatiotemporal parameters measured for patient 4. It is observed that the asymmetry in the stance time, swing time, step length and walking speed has decreased in the feedback scenario. Except the swing time, in the other three parameters increased the asymmetry in the AFI scenario but it is reduced again in the AFT scenario. However, the asymmetry of step width increases a lot in the feedback, AFI and AFT scenarios. It has to be noted that during the natural gait, step width war greater for the non-affected side than for the affected side. However, in the other scenarios, the step width was greater in the affected side than the non-affected side. (Annex 1)

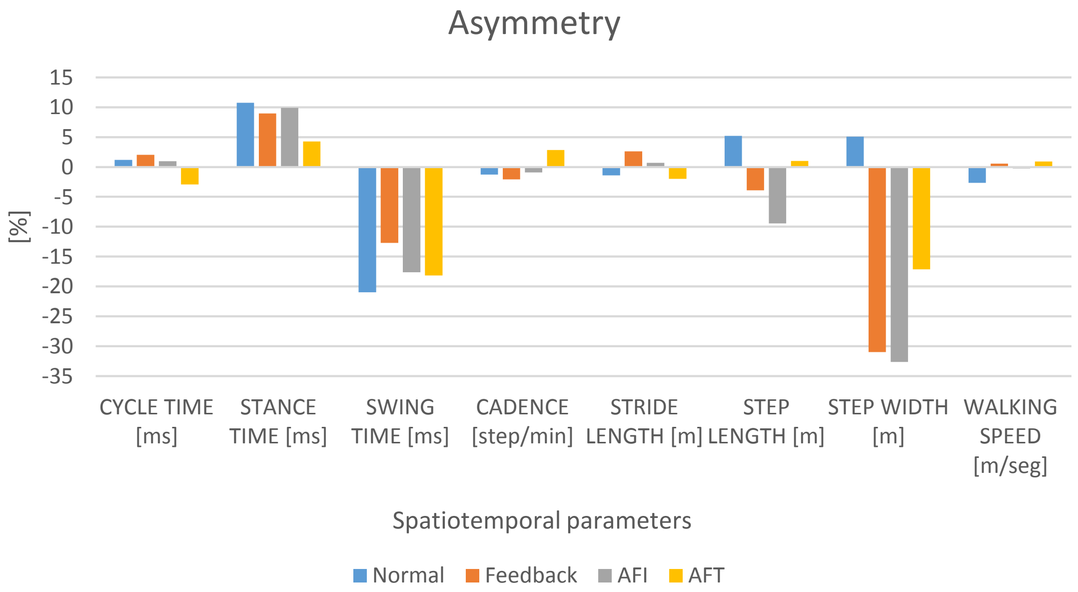


Figure 40: Asymmetry calculated with different spatiotemporal parameters for the four scenarios of Patient 4.

Figure 41 shows the hip flexion angles for the Patient 4. It is observed that the RMSE is lower in the AFI scenario. It is observed that the tendency of the affected side is more similar to non-affected side in the AFI scenarios. However, this change is not maintained in the AFT scenario.

In the knee flexion angles (Figure 42) the RMSE decreases in the AFT scenario and the tendency of the angles for both side are similar.

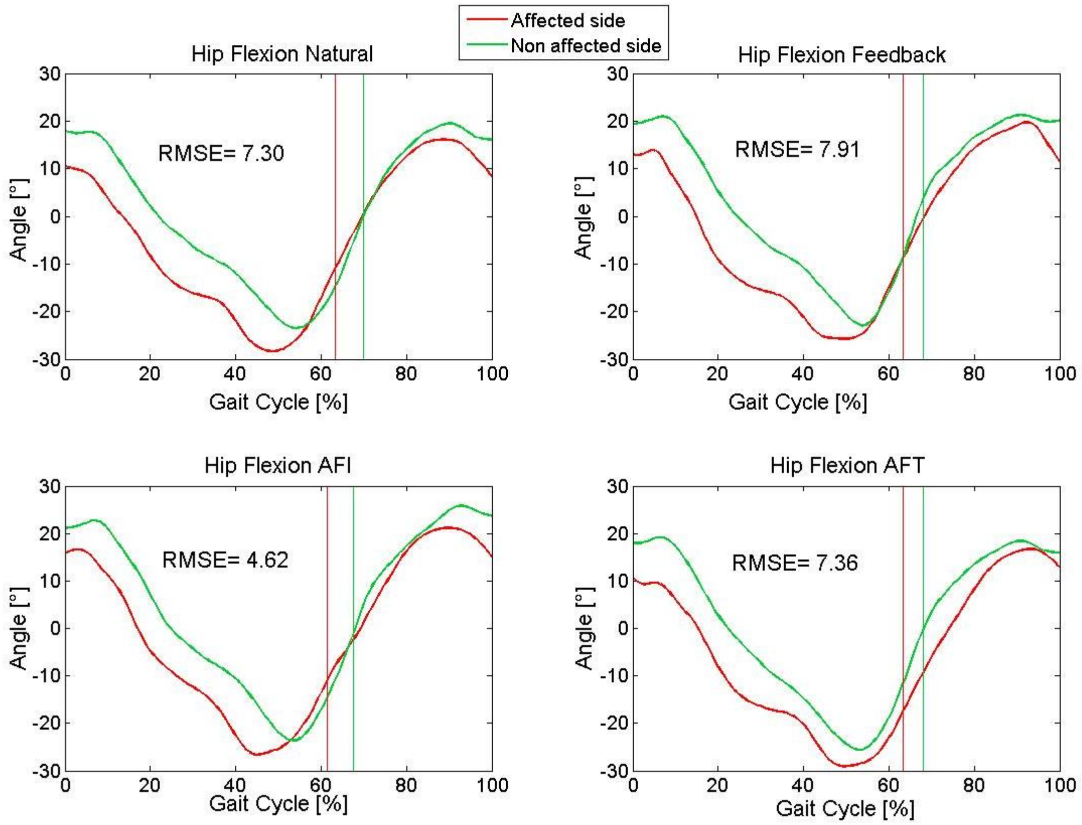


Figure 41: Hip flexion angle in affected and non-affected side measured for the four scenarios. RMSE in degrees.

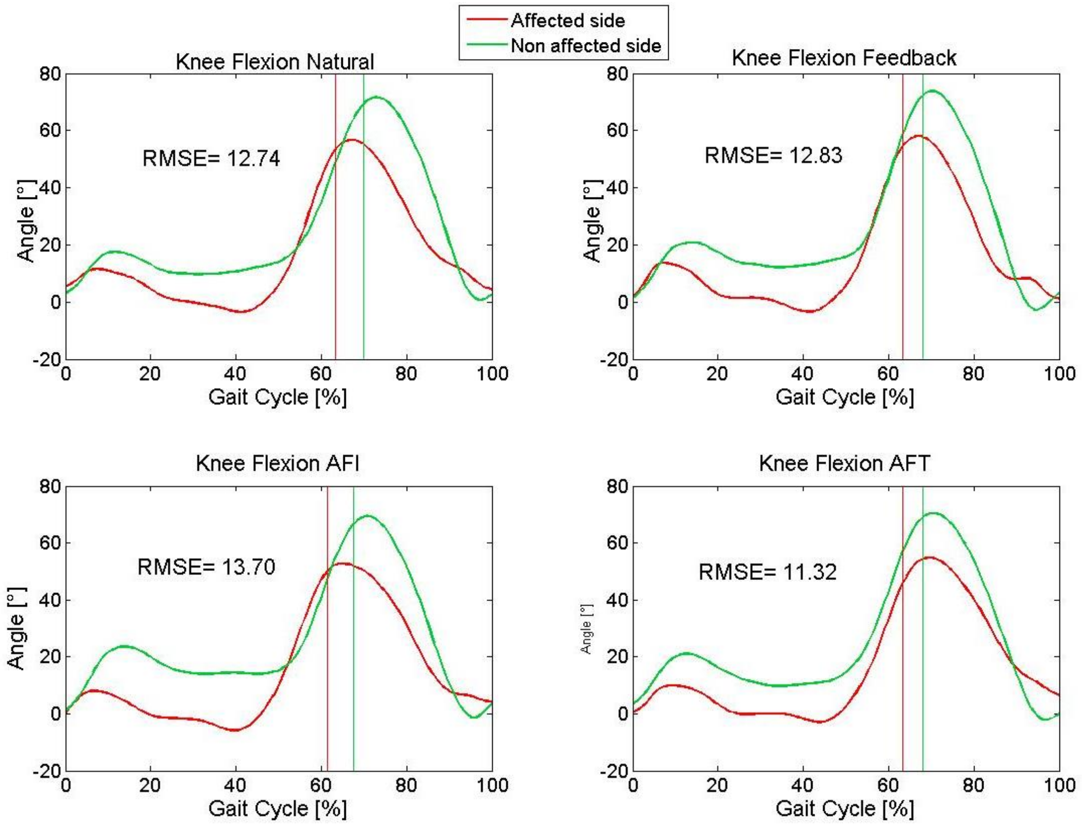


Figure 42: Knee flexion angle in affected and non-affected side measured for the four scenarios. RMSE in degrees.

Figure 43 shows Patient 4 ankle dorsiflexion angles for the Patient 4. The RMSE between non-affected side and affected side angles decreases for the different scenarios. Moreover, it is observed that the tendency of the non-affected side change in the feedback and AFI scenarios and then it recoveries the initial tendency in the AFT scenario. These change in the tendency are reflected in RMSE of the velocity angles in Table 13.

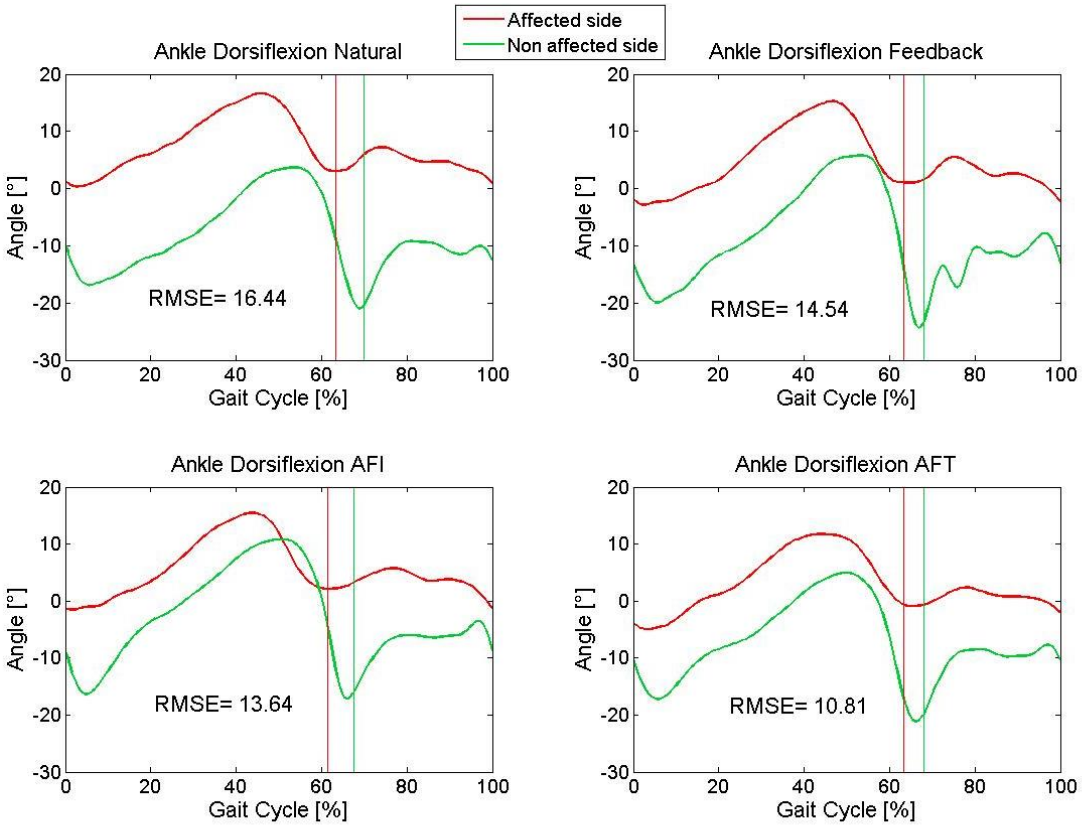


Figure 43: Ankle dorsiflexion angle in affected and non-affected side. RMSE in degrees.

Table 12 shows the peaks and the angular range of motion angular for Patient 4. It is observed that the RoM of affected hip improves a little bit for the different scenarios. However, in the AFI scenario, the affected knee RoM gets worse. Flexion is lower and the extension is greater than the feedback and natural scenarios. Finally, the RoM of the affected ankle improves a little, between 1 and 2 degrees.

Table 13 shows the RMSE calculated between the non-affected side velocity angles and affected side velocity angles. The results shows that the RMSE for the three joints are lower in the AFT scenario, meaning that Patient 4 has won control in hip, knee and ankle joints.

Patient 4		Natural		Feedback		AFI		AFT	
		Value [°]	RoM [°]	Value [°]	RoM [°]	Value [°]	RoM [°]	Value [°]	RoM [°]
Pelvis									
	Flexion	12.83	7.68	14.31	9.39	9.63	7.14	13.19	8.18
	Extension	5.14		4.91		2.49		5.01	
Hip									
Affected side	Flexion	16.06	44.42	19.72	45.48	21.15	47.80	16.71	45.78
	Extension	-28.36		-25.76		-26.65		-29.07	
Non-affected side	Flexion	19.48	42.94	21.24	44.19	25.78	49.42	19.17	44.78
	Extension	-23.46		-22.95		-23.64		-25.61	
Knee									
Affected side	Flexion	56.69	60.22	58.00	61.39	52.72	58.56	54.80	57.74
	Extension	-3.53		-3.39		-5.84		-2.93	
Non-affected side	Flexion	71.56	70.91	73.76	76.56	69.40	70.76	70.40	72.55
	Extension	0.65		-2.80		-1.36		-2.15	
Ankle									
Affected side	Dorsi flexion	16.59	16.25	15.25	18.13	15.44	16.98	11.71	16.67
	Plantar flexion	0.34		-2.87		-1.54		-4.95	
Non-affected side	Dorsi flexion	3.68	24.64	5.78	30.11	10.81	27.98	4.94	26.13
	Plantar flexion	-20.97		-24.33		-17.17		-21.19	

Table 12: Peak and range of motion angular kinematics for the four test of Patient 4.

RMSE Angular velocity [°/s]	Natural	Feedback	AFI	AFT
Hip	24.8	29.4	29.2	24.8
Knee	78.0	76.3	72.0	78.0
Ankle	48.7	62.8	49.0	48.7

Table 13: RMSE between angular velocity of non-affected side and angular velocity of affected side of Patient 4.

5. Conclusions

The present Master's Thesis of Biomedical Engineering has analyzed gait kinematics and symmetry in patients with hemiparesis using an audio feedback device. The main objective was to evaluate different measures of gait symmetry in these patients. For this reason, and according to the literature, different gait symmetry parameters have been presented and calculated.

A multibody model for the three-dimensional kinematic analysis of human gait has been used. The study has been performed using the Biomechanics Laboratory at ETSEIB, UPC. The laboratory setup and the process of learning how to use the equipment have represented a great challenge to get experience in the biomechanics field, along with all the used software: Motive, Matlab, and OpenSim.

Eight spatiotemporal parameters have been used: cycle time, stance time, swing time, cadence, stride length, step length, step width and walking speed were measured and analyzed for each patient. It has been seen that, for the 4 analyzed patients, the spatiotemporal parameters that present a higher change between the affected and non affected sides are step length, stance time and swing time. This is in agreement with (Patterson, 2010), which presents this three parameters as the most significant ones for the study of gait asymmetry. However, it has to be said that the symmetry evaluated with the step width also showed significant differences in our study. It is considered that the cadence could not be a reliable indicator for the analysis of the symmetry in the present study, since only one gait cycle is analyzed.

Moreover, joint angles, range of motion (RoM) and angular velocities have been calculated. It has to be said that the results present a great variability among the patients. Patient 1 obtains a higher RoM in the hip and knee joints, but the spatiotemporal parameters indicate that she does not achieve higher angular symmetry in any scenario. Moreover, only the RMS errors in angular velocities decrease for the feedback case, but she does not gain control in the rest of the scenarios. The results of Patient 2 show that the symmetry parameters related to time (stance and swing time) and to the angular RoM are improved. However, the parameters related to displacement present a lower symmetry. The stability of Patient 3 increases (according to the angular velocities results) but the symmetry of the main spatiotemporal parameters decreases. Finally, Patient 4 increases RoM symmetry, joint control, and the symmetry of time-related parameters (stance and swing time) as well.

By looking at the results of the project, the idea was to predict how Walking o'Clock would work in future situations with other patients. It was shown that the device decreases the asymmetry of some gait parameters, but at the same time increases it in others. However, from the obtained results, it is considered that an improvement in the angular parameters is not enough to confirm that there is an improvement in terms of the gait symmetry. That means that the therapist would have to find the most optimal feedback for each patient in order to enhance their gait. Finally, what is important to highlight is that the patients did not go back to their natural gait when stopping the device. Therefore, the device has an effect on the patient's movements.

6. Considerations and future work

This work has been developed in a biomedical environment, where physiotherapists and engineers work together. Despite having established a protocol to perform measurements in the same way in all patients, there were some factors that could not be controlled and are thought to have influenced the results. It is important to indicate such limitations in order to consider them in future works.

The instructions given to the patient to respond to the feedback were different, in some cases it was asked to increase the flexion when listening to feedback and in others to elongate the step. How this instruction affects the analyzed parameters is not clear.

On the other hand, the auditory feedback signal was chosen by the physiotherapist just at the time of the first test (from the measurement made by the devices placed on both thighs of the patient). The auditory feedback was defined for the leg with less range of motion, regardless of whether it was the affected or unaffected side. It was observed that this methodology may have been another factor of variability in the expected results with the feedback, since in some patients the feedback increased the range of motion in the non-affected leg. Moreover, it is considered that the results could be more reliable if some factors of the methodology were changed like increasing training time with the device and improving the accuracy in the auditory feedback.

Finally, the author wants to emphasize that it is important to be able to perform an interdisciplinary work, in which the technical and therapeutic vision complement each other to optimize the results.

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Annex 1

Patient 1	Natural					Feedback				
	Affected side		Non-affected side		Asymmetry	Affected side		Non-affected side		Asymmetry
	Mean	DV	Mean	DV		Mean	DV	Mean	DV	
CYCLE TIME [ms]	115,32	0,03	114,65	0,03	-0,58	120,33	0,05	118,33	0,02	-1,69
STANCE TIME [ms]	74,33	0,03	81,66	0,03	8,98	77,00	0,06	79,00	0,01	2,53
SWING TIME [ms]	41,00	0,01	33,00	1,10	-24,24	43,33	0,01	39,33	2,01	-10,17
STANCE PHASE [%]	64,44	1,06	71,21	1,10	9,51	63,93	2,23	66,78	2,01	4,27
SWING PHASE [%]	35,56	1,06	28,79	1,10	-23,51	36,07	2,23	33,22	2,01	-8,58
1st DOUBLE LIMB SUPPORT [%]	14,74	0,68	20,63	0,87	28,56	14,96	0,71	16,93	2,55	11,64
SINGLE LIMB SUPPORT [%]	29,19	0,65	36,94	0,00	20,97	32,39	1,20	36,67	0,00	11,67
2nd DOUBLE LIMB SUPPORT [%]	20,51	0,97	13,51	0,00	-51,78	16,58	1,58	13,33	0,00	-24,38
CADENCE [step/min]	104,11	2,77	104,72	2,97	0,58	99,82	3,73	101,43	1,80	1,59
STRIDE LENGTH [m]	1,28	0,02	1,27	0,02	-0,82	1,25	0,02	1,27	0,03	1,45
STEP LENGTH [m]	0,65	0,01	0,61	0,01	-6,50	0,77	0,36	0,50	0,35	-52,76
STEP WIDTH [m]	0,06	0,06	0,06	0,02	-2,37	0,07	0,05	0,17	0,08	61,96
WALKING SPEED [m/seg]	1,11	0,00	1,11	0,00	-0,23	1,04	0,00	1,08	0,00	3,02

Patient 1	After feedback immediate					After feedback training				
	Affected side		Non-affected side		Asymmetry	Affected side		Non-affected side		Asymmetry
	Mean	DV	Mean	DV		Mean	DV	Mean	DV	
CYCLE TIME [ms]	117,67	0,02	118,00	0,03	0,28	116,00	0,03	116,67	0,01	0,57
STANCE TIME [ms]	73,33	0,02	84,33	0,02	13,04	72,00	0,02	82,33	0,01	12,55
SWING TIME [ms]	44,33	0,01	33,67	1,04	-31,68	44,00	0,02	34,33	0,89	-28,16
STANCE PHASE [%]	62,32	0,71	71,47	1,04	12,80	62,07	1,12	70,57	0,89	12,05
SWING PHASE [%]	37,68	0,71	28,53	1,04	-32,07	37,93	1,12	29,43	0,89	-28,89
1st DOUBLE LIMB SUPPORT [%]	13,32	0,49	20,05	1,08	33,59	14,65	0,65	19,73	1,67	25,73
SINGLE LIMB SUPPORT [%]	28,90	0,88	37,19	0,00	22,29	27,57	1,15	38,98	0,00	29,27
2nd DOUBLE LIMB SUPPORT [%]	20,11	1,13	13,22	0,00	-52,07	19,85	1,81	13,56	0,00	-46,39
CADENCE [step/min]	102,00	1,79	101,73	2,26	-0,27	103,48	2,39	102,86	1,01	-0,60
STRIDE LENGTH [m]	1,43	0,05	1,40	0,06	-2,45	1,47	0,10	1,43	0,07	-2,45
STEP LENGTH [m]	0,75	0,03	0,65	0,02	-15,23	0,77	0,04	0,66	0,03	-15,20
STEP WIDTH [m]	0,05	0,04	0,09	0,06	44,75	0,08	0,06	0,07	0,01	-3,79
WALKING SPEED [m/seg]	1,22	0,00	1,18	0,00	-2,73	1,26	0,00	1,23	0,00	-3,07

Patient 2	Natural					Feedback				
	Affected side		Non-affected side		Asymmetry	Affected side		Non-affected side		Asymmetry
	Mean	DV	Mean	DV		Mean	DV	Mean	DV	
CYCLE TIME [ms]	118,33	0,07	116,00	0,08	-1,97	124,00	0,06	124,67	0,05	0,53
STANCE TIME [ms]	76,33	0,02	87,67	0,08	12,93	83,67	0,03	94,33	0,05	11,31
SWING TIME [ms]	42,00	0,06	28,33	1,61	-32,54	40,33	0,04	30,33	1,11	-32,97
STANCE PHASE [%]	64,60	2,83	75,50	1,61	14,44	67,51	1,40	75,65	1,11	10,77
SWING PHASE [%]	35,40	2,83	24,50	1,61	-30,80	32,49	1,40	24,35	1,11	-33,45
1st DOUBLE LIMB SUPPORT [%]	17,84	2,57	20,97	0,76	14,92	20,94	1,28	19,27	0,72	-8,65
SINGLE LIMB SUPPORT [%]	26,18	2,40	34,58	0,00	24,30	27,18	0,94	30,58	0,00	11,11
2nd DOUBLE LIMB SUPPORT [%]	20,58	1,78	18,69	0,00	-9,19	19,39	1,00	23,97	0,00	19,10
CADENCE [step/min]	101,62	5,54	103,78	7,35	2,09	96,94	4,99	96,35	3,59	-0,62
STRIDE LENGTH [m]	1,06	0,04	1,07	0,04	0,83	1,01	0,03	1,04	0,04	2,71
STEP LENGTH [m]	0,52	0,01	0,54	0,03	4,08	0,50	0,03	0,54	0,01	8,66
STEP WIDTH [m]	0,06	0,03	0,10	0,05	39,83	0,10	0,06	0,11	0,06	9,82
WALKING SPEED [m/seg]	0,90	0,00	0,92	0,00	2,90	0,82	0,00	0,83	0,00	2,11

Patient 2	After feedback immediate					After feedback training				
	Affected side		Non-affected side		Asymmetry	Affected side		Non-affected side		Asymmetry
	Mean	DV	Mean	DV		Mean	DV	Mean	DV	
CYCLE TIME [ms]	120,33	0,10	123,33	0,07	2,43	116,33	0,11	117,33	0,10	0,85
STANCE TIME [ms]	79,00	0,08	90,67	0,05	12,87	77,00	0,08	85,33	0,08	9,77
SWING TIME [ms]	41,33	0,02	32,67	0,58	-26,53	39,33	0,04	32,00	1,23	-22,92
STANCE PHASE [%]	65,58	1,25	73,53	0,58	10,81	66,16	1,43	72,72	1,23	9,02
SWING PHASE [%]	34,42	1,25	26,47	0,58	-30,03	33,84	1,43	27,28	1,23	-24,06
1st DOUBLE LIMB SUPPORT [%]	19,61	1,10	18,61	1,07	-5,39	20,66	1,01	18,42	1,28	-12,14
SINGLE LIMB SUPPORT [%]	26,89	0,78	33,33	0,00	19,33	26,92	0,49	34,82	0,00	22,68
2nd DOUBLE LIMB SUPPORT [%]	19,08	0,64	21,43	0,00	10,96	18,58	1,14	19,64	0,00	5,41
CADENCE [step/min]	100,23	8,84	97,54	6,00	-2,76	103,74	9,28	102,76	8,44	-0,95
STRIDE LENGTH [m]	1,14	0,06	1,15	0,04	1,54	1,17	0,08	1,19	0,06	2,42
STEP LENGTH [m]	0,55	0,03	0,60	0,02	7,39	0,58	0,03	0,62	0,03	6,24
STEP WIDTH [m]	0,09	0,04	0,10	0,03	11,19	0,11	0,01	0,14	0,06	24,16
WALKING SPEED [m/seg]	0,95	0,00	0,94	0,00	-1,18	1,01	0,00	1,02	0,00	1,49

Patient 3	Natural					Feedback				
	Affected side		Non-affected side		Asymmetry	Affected side		Non-affected side		Asymmetry
	Mean	DV	Mean	DV		Mean	DV	Mean	DV	
CYCLE TIME [ms]	113,00	0,06	111,00	0,04	1,77	125,67	0,07	124,67	0,07	0,80
STANCE TIME [ms]	81,67	0,04	65,00	0,04	20,41	94,00	0,05	77,67	0,06	17,38
SWING TIME [ms]	31,33	0,03	46,00	1,36	-46,81	31,67	0,02	47,00	2,70	-48,42
STANCE PHASE [%]	72,29	1,21	58,53	1,36	19,03	74,81	0,33	62,29	2,70	16,74
SWING PHASE [%]	27,71	1,21	41,47	1,36	-49,64	25,19	0,33	37,71	2,70	-49,73
1st DOUBLE LIMB SUPPORT [%]	20,63	0,88	10,79	1,59	47,68	23,54	1,95	13,64	1,46	42,06
SINGLE LIMB SUPPORT [%]	41,07	2,03	27,10	0,00	34,01	37,74	2,68	25,76	0,00	31,75
2nd DOUBLE LIMB SUPPORT [%]	10,59	1,35	20,56	0,00	-94,22	13,53	1,55	22,73	0,00	-67,92
CADENCE [step/min]	106,41	5,91	108,19	3,56	-1,67	95,67	4,98	96,46	5,40	-0,83
STRIDE LENGTH [m]	1,16	0,02	1,15	0,03	0,85	1,05	0,04	1,04	0,04	0,62
STEP LENGTH [m]	0,58	0,02	0,57	0,03	2,72	0,51	0,03	0,54	0,02	-6,32
STEP WIDTH [m]	0,13	0,02	0,13	0,04	4,37	0,15	0,00	0,23	0,04	-59,76
WALKING SPEED [m/seg]	1,03	0,00	1,04	0,00	-0,81	0,84	0,00	0,84	0,00	-0,20

Patient 3	After feedback immediate				
	Affected side		Non-affected side		Asymmetry
	Mean	DV	Mean	DV	
CYCLE TIME [ms]	112,00	0,08	113,33	0,09	-1,19
STANCE TIME [ms]	80,33	0,04	60,33	0,08	24,90
SWING TIME [ms]	31,67	0,04	53,00	11,02	-67,37
STANCE PHASE [%]	71,78	1,36	53,84	11,02	25,00
SWING PHASE [%]	28,22	1,36	46,16	11,02	-63,58
1st DOUBLE LIMB SUPPORT [%]	20,86	0,81	12,33	0,51	40,90
SINGLE LIMB SUPPORT [%]	38,45	1,36	29,36	0,00	23,64
2nd DOUBLE LIMB SUPPORT [%]	12,48	0,81	18,35	0,00	-47,08
CADENCE [step/min]	107,46	7,16	106,34	8,35	1,05
STRIDE LENGTH [m]	1,17	0,10	1,13	0,08	2,98
STEP LENGTH [m]	0,58	0,05	0,55	0,03	3,75
STEP WIDTH [m]	0,16	0,00	0,19	0,01	-20,52
WALKING SPEED [m/seg]	1,04	0,00	1,00	0,00	4,00

Patient 4	Natural					Feedback				
	Affected side		Non-affected side		Asymmetry	Affected side		Non-affected side		Asymmetry
	Mean	DV	Mean	DV		Mean	DV	Mean	DV	
CYCLE TIME [ms]	109,67	0,06	111,00	0,05	1,20	112,33	0,03	114,67	0,03	2,03
STANCE TIME [ms]	69,33	0,02	77,67	0,05	10,73	71,00	0,01	78,00	0,01	8,97
SWING TIME [ms]	40,33	0,04	33,33	2,69	-21,00	41,33	0,02	36,67	0,64	-12,73
STANCE PHASE [%]	63,27	1,38	69,96	2,69	9,57	63,22	0,97	68,03	0,64	7,07
SWING PHASE [%]	36,73	1,38	30,04	2,69	-22,30	36,78	0,97	31,97	0,64	-15,06
1st DOUBLE LIMB SUPPORT [%]	15,19	0,58	18,06	1,54	15,85	14,56	1,26	19,19	0,80	24,14
SINGLE LIMB SUPPORT [%]	29,79	1,76	35,71	0,00	16,60	29,07	1,42	37,39	0,00	22,25
2nd DOUBLE LIMB SUPPORT [%]	18,29	1,65	14,29	0,00	-28,00	19,59	1,02	12,17	0,00	-60,95
CADENCE [step/min]	109,61	5,54	108,23	4,53	-1,27	106,87	2,79	104,68	2,31	-2,09
STRIDE LENGTH [m]	1,06	0,05	1,05	0,05	-1,39	1,14	0,05	1,17	0,04	2,60
STEP LENGTH [m]	0,51	0,03	0,54	0,03	5,21	0,59	0,04	0,57	0,01	-3,91
STEP WIDTH [m]	0,11	0,10	0,12	0,03	5,09	0,11	0,03	0,08	0,02	-31,00
WALKING SPEED [m/seg]	0,97	0,00	0,95	0,00	-2,68	1,01	0,00	1,02	0,00	0,56

Patient 4	After feedback immediate					After feedback training				
	Affected side		Non-affected side		Asymmetry	Affected side		Non-affected side		Asymmetry
	Mean	DV	Mean	DV		Mean	DV	Mean	DV	
CYCLE TIME [ms]	103,67	0,01	104,67	0,03	0,96	106,00	0,04	103,00	0,04	-2,91
STANCE TIME [ms]	63,67	0,02	70,67	0,01	9,91	67,00	0,01	70,00	0,02	4,29
SWING TIME [ms]	40,00	0,02	34,00	1,79	-17,65	39,00	0,05	33,00	2,35	-18,18
STANCE PHASE [%]	61,41	1,99	67,54	1,79	9,08	63,28	2,91	68,02	2,35	6,96
SWING PHASE [%]	38,59	1,99	32,46	1,79	-18,89	36,72	2,91	31,98	2,35	-14,80
1st DOUBLE LIMB SUPPORT [%]	11,91	1,24	16,91	1,85	29,58	14,19	2,03	16,57	3,05	14,32
SINGLE LIMB SUPPORT [%]	32,46	1,65	38,10	0,00	14,78	32,98	2,43	37,74	0,00	12,60
2nd DOUBLE LIMB SUPPORT [%]	17,04	1,46	11,43	0,00	-49,11	16,11	3,02	13,21	0,00	-21,96
CADENCE [step/min]	115,77	1,28	114,69	2,77	-0,93	113,34	4,77	116,65	5,05	2,84
STRIDE LENGTH [m]	1,22	0,05	1,22	0,10	0,69	1,21	0,12	1,18	0,11	-1,98
STEP LENGTH [m]	0,64	0,06	0,58	0,04	-9,47	0,59	0,07	0,60	0,04	1,02
STEP WIDTH [m]	0,16	0,04	0,12	0,07	-132,99	0,14	0,02	0,12	0,01	-17,12
WALKING SPEED [m/seg]	1,17	0,00	1,17	0,00	-0,24	1,14	0,00	1,15	0,00	0,92