

Assistive Technology for Patient with Congenital Foot Deformity

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Abstract. An assistive technology (AT) is any item, equipment or product used to increase, maintain or improve the functional capabilities of people with disabilities. The aim of this study was to design and develop two ATs in order to assist the needs of a male student from Universidad de Monterrey experiencing gait dysfunction and pain due to a congenital foot deformity preventing him from normal performance. These ATs included personalized orthopedic insoles to improve the participant's posture and stability as well as two ankle-foot orthosis (AFO) to reduce the pain he presented. In order to design the orthopedic insoles, it was necessary to scan the participant's feet; this was achieved using the photogrammetry technique. For the design of the AFOs, anthropometric measurements of the lower limbs were taken in order to modify a predefined 3D human model and obtain a digital model of the lower limbs. Both devices were manufactured using 3D printing technology. In order to analyze the participant's progress and validate the effectiveness of the ATs, we developed a methodology for movement analysis based on the marker-less motion capture system Kinect 2. Data obtained was imported into Matlab in order to calculate lower limb joint angles and compare gait before and after using the ATs. Significant improvement was seen in the participant's gait after two weeks of using the ATs. Moreover, we were able to demonstrate that the use of orthopedic insoles improved participant's posture based on the correct alignment (180°) of the heel with the ankle. We believe these posture improvements could further impact on participant's gait performance. Therefore, we expect a significant improvement on participant's gait after constant use of both ATs developed.

1. Introduction

According to 2014 data from the INEGI, 7.2 millions of Mexicans (6% of Mexico's total population) suffer from some type of disability. The most reported among the population with a 64.1% was the motor disability [1]. According to the World Health Organization, more than one billion people with disabilities in the world need an assistive technology. An

assistive technology is any device used by a person who has some type of disability to improve their functional capacity [2]. However, only 10% of the population has access to them. It is expected that by 2050 more than 2000 million people will require one or more assistive technology [3]. In this study, it was proposed to carry out an evaluation of a patient experiencing gait dysfunction and pain due to a congenital foot deformity in order to select the most appropriate assistive technology that best suits his needs.

2. Methodology

The methodology that was followed for this project was divided into three main phases: the development of assistive technology, the development of a methodology for a motion analysis system and the validation of the assistive technology.

2.1 Development of assistive technology

The process of the development of assistive technology was divided into advice and evaluation by health experts, design of assistive technology which consists of design of orthopedic insoles and ankle-foot orthosis and finally, the fabrication of both ATs using the 3D printing technology.

2.1.1 Advice and evaluation by health experts

Expert advice was critical for our project. By means of x-rays physicians diagnosed the patient with a congenital foot deformity known as plano-valgus foot. Moreover, based on patient's pain experience in his heel when he first gets up in the morning and starts walking, physicians also diagnosed the condition of plantar fasciitis. Based on the health experts diagnosis and advice, it was decided to develop two assistive technologies. The first one, a pair of orthopedic insoles to improve the participant's posture and stability, the second, a pair of ankle-foot orthosis to treat the plantar fasciitis condition.

2.1.2 Design of orthopedic insoles

For the design of the orthopedic insoles for plano-valgus foot, four steps were followed. These steps included: obtaining the feet molds, the scanning, the use of specialized software and finally the material selection. To obtain the molds of the patient's feet a series of steps were followed. An alginate mixture was made to cover the patient's feet and afterwards, a plaster mixture was poured into the alginate mold and once it dried, we proceeded to unmold it. The final product obtained was a plaster replica of both patient's feet. After obtaining the molds, the scanning of the plantar surface of the patient was done. For this a technique known as photogrammetry was used, which allows to create 3D models through multiple photographs taken from different angles [4].

Once the images were captured, they were imported into a specialized software called Agisoft Metashape (Agisoft LLC, St. Petersburg, Russia). In this program, the images taken were aligned which allowed us to observe the camera path followed around the object of interest. With this information the creation of a dense point cloud could be achieved and allowed the construction of a mesh which is a high-resolution 3D model where all the points of the dense cloud are connected [5].

After obtaining the scan of the patient's feet, a software called Rhino 3D (Robert McNeel & Associates, Miami, USA) was used with the LutraCAD plugin (LutraCAD B.V., Veghel, Nederland), a specialized software for the design of orthopedic insoles. The software automatically generated the contour around each feet (Fig. 1a) and the program allowed us to manually adjust this contour to exactly fit the surface of the feet (Fig. 1b).

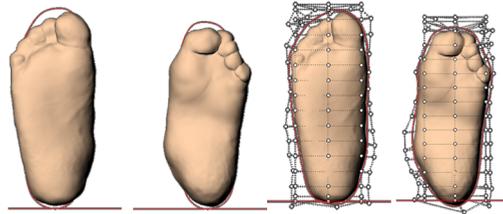


Fig. 1. a) Orthopedic insoles contour b) Orthopedic insoles contour adjusted

And finally, to be able to carry out the manufacturing process, the selection of materials had to be done. For this purpose, a comparative table (Table 1) of different materials was made, evaluating hardness, deformation, flexibility and durability [6]. For the material of the orthopedic insoles it was necessary a flexible material for greater comfort of the patient, as well as a minimum deformation to maintain the geometry of the plantar surface. Also, since the orthopedic insoles would be of daily use it was required a high durability to avoid the wearing out of these. Taking this into consideration, the best option to use was the thermoplastic polyurethane filament also known as TPU since it met all the necessary requirements.

Table 1. Comparative table of 3D printing filaments.

	PLA	TPU/TPE	PETG
Hardness	High	Medium	High
Deformation	Minimum	Minimum	Minimum
Flexibility	Low	Very high	Medium
Durability	Medium	Very high	High

2.1.3 Design of ankle-foot orthosis

An orthosis is a device external to the human body that serves to modify both functional and structural aspects. For the design of the ankle-foot orthosis different steps were followed including: taking measurements of the patients' lower limbs, generating the 3D model, the use of specialized software and finally the selection of material. Anthropometric measurements taken included the diameter of the knee, calf and ankle as well as the height between the knee and the ankle for both the right and left lower limbs. These measurements were necessary so that when designing the ankle-foot orthosis it could be adapted as best as possible to the geometry of the patient's lower limbs. Once the measurements were taken, a 3D model of human being was generated using a software called Makehuman. This software

is parameterized and allowed us to modify measurements at specific points, such as the ones taken in our study and previously described.

The 3D model obtained was then exported to a specialized software called Blender (Blender Foundation, Amsterdam, Nederland). It was decided to cut the model to only have the lower limbs since those were the ones of our interest. This model of the lower limbs was our base model to be able to design the ankle foot orthosis around it. A plugin called dual mesh was applied to the structure to give an aspect of mesh-shaped cells. One of the benefits of using this plugin was that less material was required therefore the orthosis would be lighter.

Finally, it was necessary to select the material of the orthosis and for this the same comparative table (Table 1) as the one for the orthopedic insoles was used. A material with high hardness was required since it was sought that the orthosis could maintain the foot in a specific position. It also had to have a minimum deformation to maintain the design structure. Considering these specifications, the polylactic acid filament material also known as PLA was selected. The PLA, besides being cheap and easy to get, can be biodegradable.

2.1.4 3D printing

Once the final designs of each assistive technology were obtained, the manufacturing process was carried out using the 3D printing technology. The final product of the orthopedic insoles for plano-valgus foot using the blue TPU filament can be observed in Fig. 2a. The final result of the ankle-foot orthosis using the PLA filament can be observed in Fig. 2b.



Fig. 2. a) Orthopedic insoles b) Ankle-foot orthosis

2.2 Development of methodology for a motion analysis system

The gait is the pattern of a person's manner of walking. It is a series of alternating and rhythmic limb and trunk movements [7] that is divided into two phases. The first one is called stance phase and begins once the heel of the reference leg meets the ground. This phase constitutes approximately 60% of the gait. The second phase is called swing phase and begins when the leg is raised and oscillates in the air preparing for its next contact with the ground. This phase constitutes approximately 40% of the gait [8].

Gait analysis is the study of the movement of the human body that allows the identification of gait characteristics of each individual and based on these it could be diagnosed any pathology or dysfunction of the lower extremities that can be treated by specialists [9]. Currently, there are various technologies available on the market to be able to carry out a gait analysis. Existing technologies allow the use of a technique known as motion capture (MoCap) which consists of recording the movements of a human and digitize them [10]. Different systems are identified in the literature that are used to capture the movement of the human body, including the optical and non-optical systems. The optical systems are

divided into those in which markers are used and those marker-less [11]. For this project a marker-less optical sensor, the Kinect 2.0 sensor, was used. The data obtained by the depth camera is processed to generate the position of each joint and store them in coordinates (x, y, z).

After understanding gait, motion capture, and gait analysis the development of the methodology for a motion analysis system could be done. This phase was divided into three different stages which included: motion capture, data processing and gait analysis. For the motion capture, a software called IPIsoft (Michael Nikonov, Moscow, Russia) was used; this included two different programs. IPIRecorder was used to record the patient's gait using the Kinect Sensor. Once this recording was obtained, it was analyzed using the IPI mocap studio program with the biomech plugin. To begin recording, the initial position of the subject had to be in T-pose so that the software could recognize the human body as observed on Fig. 3. The sensor was placed 3.8 meters apart from the patient in order to allow him to walk a distance of 2.3 meters without leaving the sensor's range of vision. It is worth mentioning that this protocol was also performed by a sex and age-matched control presenting no alteration in his gait. For both participants, patient and control, a complete cycle including stance and swing phases were recorded in order to compare and observe differences among the two participants.



Fig. 3. Kinect set-up

Once the motion capture was done, the recording was exported to the IPI mocap Studio software where the processing of the acquired data took place. In the software, two models were generated: the patient's motion model and our base model. This second one had to be adjusted to the patient's model. The biomech plugin was used to select the desired joints that were going to be analyzed. For our project we only focused on the joints of the lower limbs which included knees and feet angles. Afterwards, we exported the data in .mat format; this was a matrix of the position coordinates of the selected joints. This matrix was used in Matlab 2018b (MathWorks, Massachusetts, USA) to carry on the gait analysis.

Once having the imported data matrix in Matlab 2018b (MathWorks, Massachusetts, USA) containing position coordinates in the space (x, y, z) of the selected bones, the angles between different segments were calculated. In Matlab 2018b (MathWorks, Massachusetts, USA), a programming code was developed so that it would be able to automatically calculate the angles between segments. First, the vectors representing the segments between two points were obtained, using the following formula:

$$A = [x_1 \ y_1 \ z_1]$$

$$B = [x_2 \ y_2 \ z_2]$$

$$C = [x_3 \ y_3 \ z_3]$$

$$D = [x_4 \ y_4 \ z_4]$$

$$\overrightarrow{AB} = \langle x_2 - x_1 \ y_2 - y_1 \ z_2 - z_1 \rangle$$

$$\overrightarrow{CB} = \langle x_2 - x_3 \ y_2 - y_3 \ z_2 - z_3 \rangle$$

$$\overrightarrow{BC} = \langle x_3 - x_2 \ y_3 - y_2 \ z_3 - z_2 \rangle$$

$$\overrightarrow{DC} = \langle x_3 - x_4 \ y_3 - y_4 \ z_3 - z_4 \rangle$$

For the gait analysis it was necessary to calculate the angle of the knee and the foot, that's why we had to create different segments. We used vectors to represent the segments; the vectors created were AB representing the thigh, BC representing the leg and CD representing the foot as observed in Fig 4.

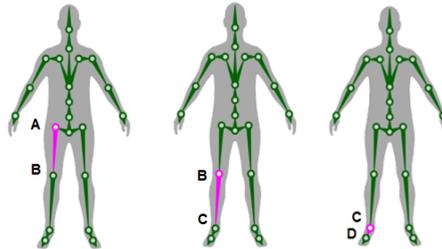


Fig. 4. Body segments

Once these vectors were calculated we could obtain the angles between the vectors. We obtained two different angles: theta representing angle between thigh and leg (Fig 5a), and phi representing angle between leg and foot (Figure 5b).

$$\begin{aligned} \|\overrightarrow{AB}\| &= \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} & \|\overrightarrow{BC}\| &= \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2} \\ \|\overrightarrow{CB}\| &= \sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2 + (z_2 - z_3)^2} & \|\overrightarrow{DC}\| &= \sqrt{(x_3 - x_4)^2 + (y_3 - y_4)^2 + (z_3 - z_4)^2} \\ \theta &= \cos^{-1}\left(\frac{\overrightarrow{AB} \cdot \overrightarrow{CB}}{(\|\overrightarrow{AB}\|)(\|\overrightarrow{CB}\|)}\right) & \Phi &= \cos^{-1}\left(\frac{\overrightarrow{BC} \cdot \overrightarrow{DC}}{(\|\overrightarrow{BC}\|)(\|\overrightarrow{DC}\|)}\right) \end{aligned}$$

Fig. 5. a) Angle between thigh and leg b) Angle between leg and foot.

Once all the angles were calculated, they were saved in a struct to be able to graph them in MATLAB where the angles between the thigh-leg and leg-sole of the foot were compared for a normal and an abnormal gait.

2.3 Validation of assistive technology

For the validation through segment alignment with respect to the orthopedic insoles we had to observe the angle variation before and after the use of insoles. The initial position of the patient's feet without insoles caused its plantar surface to be turned outwards, away from the mid-plane of the body. We used Kinovea (Joan Charmant, Bordeaux, France) to mark the reference points. What was sought was to approach the desired value that was 180 degrees

indicating a correct alignment and indeed we can observe (Fig 6) the angle decreased from 198 to 192 on the left foot and from 191 to 183 on the right foot both approaching 180. Making the comparison we concluded that the orthopedic insoles were effective since they allowed better alignment of the heel with the ankle of the patient's feet.

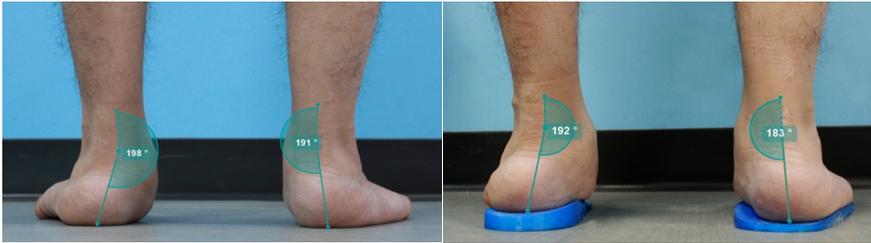


Fig. 6. Angles between heel and ankle a) Without using insoles b) Using insoles

For the validation of the ankle foot orthosis we observed the angle variation before and after the use of it. When the patient was not using the orthosis there was an angle of 129 degrees (Fig 7a). There was a lot of tension in the thick connective tissue causing plantar fasciitis therefore pain on the plantar surface. What was sought was to decrease this angle. On the other hand, the angle obtained when using the orthosis decreased to 118 degrees (Fig 7b) which proved its effectiveness. It is concluded that the use of assistive technology corrected the foot drop around 11 °.



Fig. 7. Angle a) Without using AFO b) Using AFO

3. Results

For the validation of the assistive technology through gait analysis we used the software Matlab 2018b (MathWorks, Massachusetts, USA). Here we developed a programming code to calculate the angles of the knee and feet during the different gait phases. First, we had to analyze our control gait which was our reference. This was a gait of a patient who had no alterations on his feet. This reference helped us to compare it against the patient's gait and clearly observe the differences among them. The code developed allowed us to visualize a window with two graphs and an animation. In the graphs we observe the flexion angle of the knees and the feet of both legs. The animation represents the patient walking. Also, in the graphs we can observe on the x-axis, where the frames per second are located, the division between stance (blue) and swing phases (red) of the patient's gait. In Fig 8 in the upper left graph showing the knee and foot angles during different phases of the walk we observe two lines of data; the blue line refers to the angle of the right knee while the green line refers to the angle of the right foot the same with the upper right graph showing data from left knee and foot.

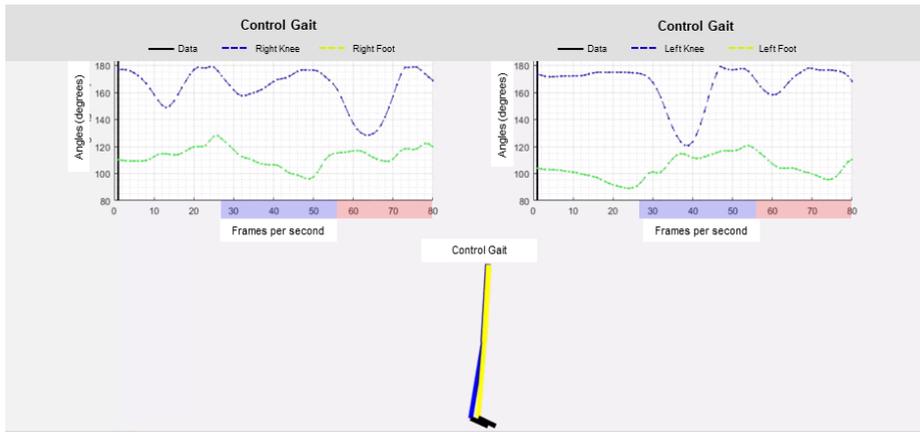


Fig. 8. Matlab window showing normal gait angles.

After analyzing our control gait, we proceeded to analyze the progress of the patient's gait through the weeks. Comparing control gait against patients gait week 0 (Fig 9) we found that the patient had very little flexion on his knees due to his condition. Another difference that we could observe were the frames per second; in our control gait we have 80 frames per second while in the patient's gait week 0 we have 45 frames per second meaning that the patient finishes a complete gait cycle in half the time of the gait control, this occurs since the patient does not have sufficient stability and therefore his steps are shorter.

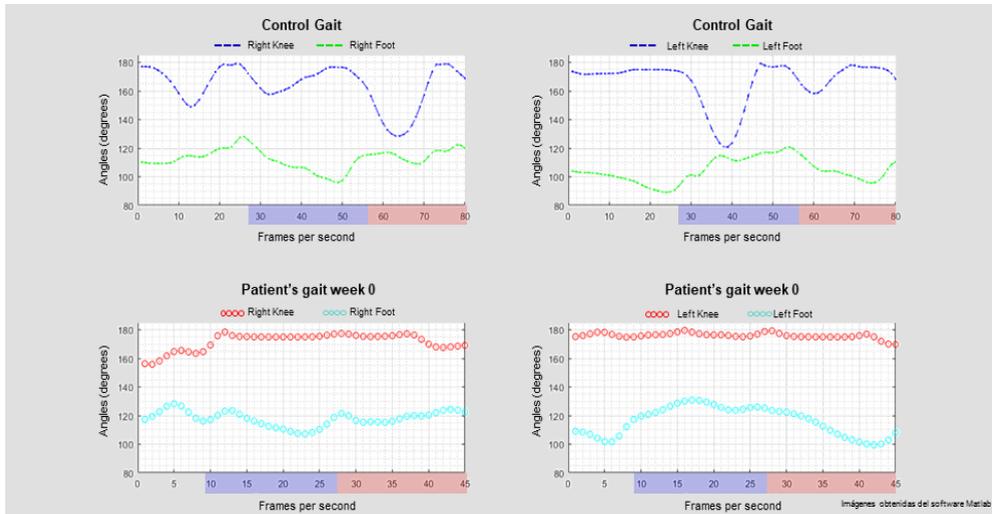


Fig. 9. Comparison control gait and patient's gait week 0 on Matlab.

Once the patient started using the orthopedic insoles, we evaluated his progress one week after and compared it to the results obtained in week 0 (Fig 10). The patient's knee flexion angle went from 160 degrees in week 0 to 180 degrees in week 1, which means the right knee is fully extended while standing before walking. Moreover, a second difference found was that his left knee begins to have more flexion angles. Finally, the frames per second differ from week 0 to week 1, longer in week 1, which means that the patient started to feel more stable and to take longer steps. Afterwards, the patient's gait was evaluated after two

weeks using the orthopedic insoles and compared it to the results from week 1. Among the differences one of the most notable were the angles of flexion of the knee on both legs.

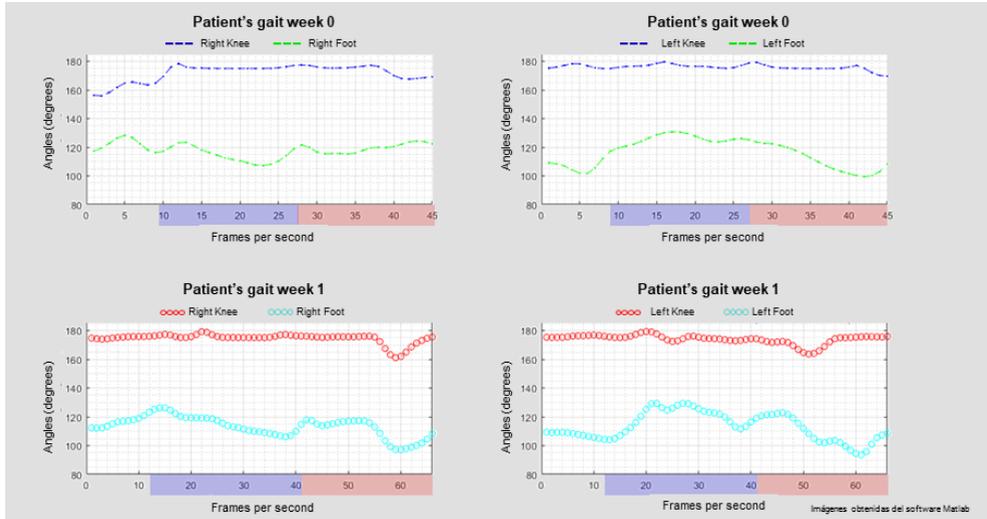


Fig. 10. Comparison patient's gait week 0 and week 1 on Matlab.

Because our methodology was extensive, we were just able to evaluate two weeks after the patient started using the orthopedic insoles. That's why for the last step of our analysis we decided to compare our control gait with the patient's gait week 2 (Fig. 11). In both gaits we observe a flexion angle of the right knee at the beginning of the gait which is a positive result. Similarly, there is an angle of flexion in the right knee at the moment that the swing phase begins, both in the control gait and in the patient's gait. Also, we observe an angle of flexion in the left knee during the stance phase in both gaits. All these results were obtained from the motion analysis system and based on these results we could conclude that the orthopedic insoles were showing positive changes in the patient's gait.

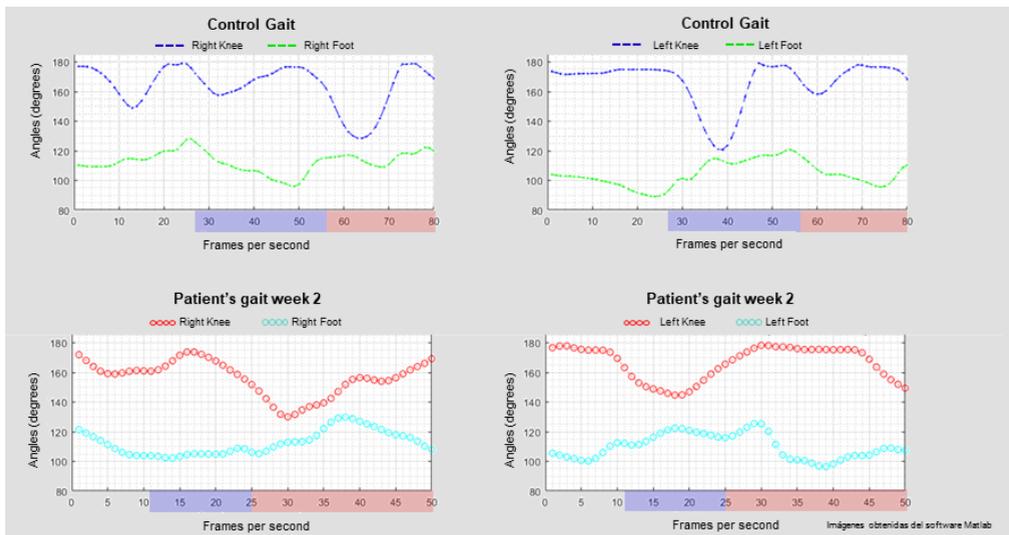


Fig. 11. Comparison control gait and patient's week 2 on Matlab.

4. Conclusion

The expectations of the project developed in its essential parts were met: the 3D design of the assistive technology and the development of the methodology for the motion analysis system. For the assistive technologies, adjustments should be considered in the future since both functional and structural changes will occur and therefore insoles will need modifications to adapt correctly to the new needs of the patient's foot. The development of the methodology for the analysis of movement in this case was used to acquire the angles of the joints of the lower limbs. However, the developed methodology can be used to acquire angles of any joint of the human body and to validate different assistive technologies apart from those designed in this project.

5. References

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