COB-2021-1002
DEVELOPMENT OF A SYSTEM FOR BIOMECHANICAL ASSESSMENT OF HUMAN GAIT IN CLINICAL SETTINGS

Jordana Simões Ribeiro Martins
Bruno Petrocchi de Sena Azevedo
Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Avenida Dom José Gaspar, 500 – Coração Eucarístico, Belo Horizonte – MG, 30535-901, Brazil
martinsjsr@gmail.com
brunoptcsa@gmail.com

Claysson Bruno Santos Vimieiro
Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Avenida Dom José Gaspar, 500 – Coração Eucarístico, Belo Horizonte – MG, 30535-901, Brazil
Department of Mechanical Engineering, Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627, Pampulha – MG, 31270-901, Brazil.
claysson@pucminas.br

Abstract. *Walking is a locomotion motor skill that allows the movement of the body in space through a sequence of coordinated actions of the articular segments of the upper, lower and trunk members. Currently, gait analysis is done through observational techniques, subjectively, and depends on the skills and experiences of health professionals to try to identify and describe the disorders of the body segments. The present project proposes the development of a system to assist in the biomechanical evaluation of gait based on a low-cost instrumented treadmill with a force plate together with a motion capture system, aiming at the quantification of the kinetic and kinematic parameters that characterize the individual's gait. The instrumented treadmill will allow the measurement of ground reaction forces from two force platforms installed directly on the conveyor. The mapping of the displacements of the body segments during the walk will be carried out using the Kinect sensor. The analysis of these data will assist health professionals in diagnoses and treatments related to gait.*

Keywords: *Kinect sensor, Instrumented treadmill, Biomechanical gait assessment.*

1. INTRODUCTION

Bipedal walking is the natural mode of locomotion of the human being combining the posture balance in a vertical position and its propulsion, bringing into play in an agreed manner and alternate the two lower limbs. Walking is a cyclic motor activity that alternates between a stance phase (foot ipsilateral in contact with the ground) and an oscillating phase (ipsilateral foot in flight phase). A walking cycle is thus composed of a support phase (about 60% of the cycle) and an oscillation phase (about 40% of the cycle) of the right and left lower limbs (Perry and Schoneberger 1992).

The decrease in mobility following a pathology most often leads to a decrease in functional capacities and consequently isolation from social life. Therefore, the rehabilitation of walking is the subject of special attention on the part of health professionals.

Gait analysis began as an observation skill of clinical staffs, therapists, and orthotic and prosthetic technicians, who recognize the normal properties of the lower limbs and the events of contact with the ground (Rose and Gamble, 2007).

Analysis of walking through the human eye is a method still used in the medical world, mainly because it is an inexpensive procedure requiring few resources to none (Eltoukhy *et al*. and Caparelli, 2017). However, there are movements that the human eye cannot perceive in a short time and therefore, the visual analysis must be associated with objective assessments (Springer *et al.*, 2016, Dolatabadi *et al*., 2016, and Caparelli, 2017).

For the evaluation of pathologies related to a human gait, it is common to use video tools, a stopwatch, among others, together with visual assessment. Tinetti et al. (Tinetti *et al.*, 1993) showed the tests commonly used during consultation with patients in the office: the "ten-meter walk" test where the clinical staff calculates the number of steps and/or keep track of the time to complete this task; the "up and go" test where the clinical staff calculates the time taken by the person to sit down, get up, walk 3 m and come back to sit; the test of "duration of the unipedal support" where the clinical staff calculates the time during which the no one balances on one foot without standing; the "comfortable walking speed" test where the clinical staff calculates the patient's speed walking "normally"; the "Tinetti" test allowing, using a questionnaire and small exercises, to judge the quality of walking and balance.

The development of new technologies has made it possible to introduce numerous techniques for analyzing human gait in a clinical, both to understand the impact of certain pathologies on locomotor function than to assess the effect of rehabilitation on the quality of walking.

Silva et al. (Silva *et al.*, 2002) proposed the use for gait assessment systems to: study the normal or pathological walking of the person in the medical field or in biomechanics; to analyze the body in activity in the field of sport; to study the influence of different devices on ergonomic walking; to analyze the humanoid walk-in order to understand it and reproduce it in the robotics framework; to simulate walking and integrate it into virtual characters in the field of animation and synthesis simulation. The common objective is to quantify walking and to analyze it in a spatial-temporal context.

In the optoelectronics systems, the main system of measurement of movement treated in this study, the volunteers are positioned in the field of view of the cameras that capture the light emitted by the sensors placed on the anatomical points of the human body. The main optoelectronic systems are: Vicon Nexus (Tanaka *et al*., 2018, Eltoukhy *et al*., 2017, Auvinet *et al*., 2017, Macpherson *et al*., 2016, and Müller *et al*., 2017), OptiTrack, (Dubois *et al*., 2018), Qualisys 100 Hz (Vimieiro *et al*., 2015). Optoelectronic systems remain fairly restrictive and expensive. With each new installation system, a calibration phase is necessary to define a common reference between all cameras and inform them of their position in relation to each other. Like any system with onboard sensors, the positioning of the sensors or markers depends on their installation and can be moved while walking. In addition, some markers may be obscured by body segments. To correctly analyze the movement of the person, a 3D array of cameras is usually required.

Low-cost alternatives have emerged to popularize and improve movement analysis in clinics, of which the following stand out: the Kinect One - no longer marketed by the manufacturer (Martins *et al*. 2019, Martins *et al*. 2021, Tan *et al*., 2019, Eltoukhy *et al*., 2017, Macpherson *et al*., 2016, and Auvinet *et al*., 2017); and the Azure Kinect (Liao *et al*, 2020); commercial cameras (Caparelli *et al*., 2017).

The forces external to the human body during locomotion are calculated through kinetic analysis. Those are the force of gravity and the ground reaction force (GRF), which represent the physical interactions between the body and the environment (Cappozzo, 1984). The GRF can be accurately estimated by experimental measurements using force platforms, however, it is limited to the number of platforms installed in the laboratory (Hulle *et al*., 2020). For data collection of countless strides, it is used instrumented mats with force platforms associated with other data collection technologies (Forner-Cordero *et al*., 2006, Edginton *et al*., 2007, and Hong *et al*., 2017).

The goal of this paper is the development of a low-cost system to assist in the biomechanical evaluation of human gait, based on an instrumented treadmill with force plates together with a Kinect sensor as a motion capture system, aiming at the quantification of the kinetic and kinematic parameters that characterize a gait.

2. METHODOLOGY

The conventional treadmill is instrumented with force plates, positioned beneath the mat to collect GRF data, and accompanied with a Kinect sensor for visually capturing the movement. Figure 1 shows the configuration of the treadmill.

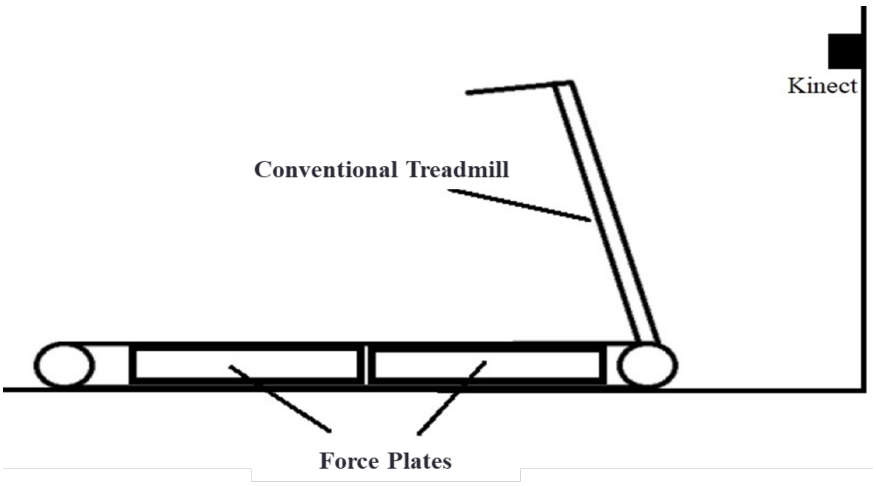


Figure 1. Configuration of the instrumented treadmill

To acquire kinematics, a motion acquisition system based on the Microsoft Kinect One sensor its placed on a position with a clear view of the subject. Configurations like this have already been used in the analysis of several studies related to gait (Tan *et al*., 2019, Eltoukhy *et al*., 2017, Macpherson *et al*., 2016, and Auvinet *et al*., 2017).

The equipment will acquire the coordinates in real time of 25 mapping of points of interest and their coordinates in relation to the 3D coordinate system of the Kinect (Adikari et al., 2017), which correspond to the main joints of the human body.

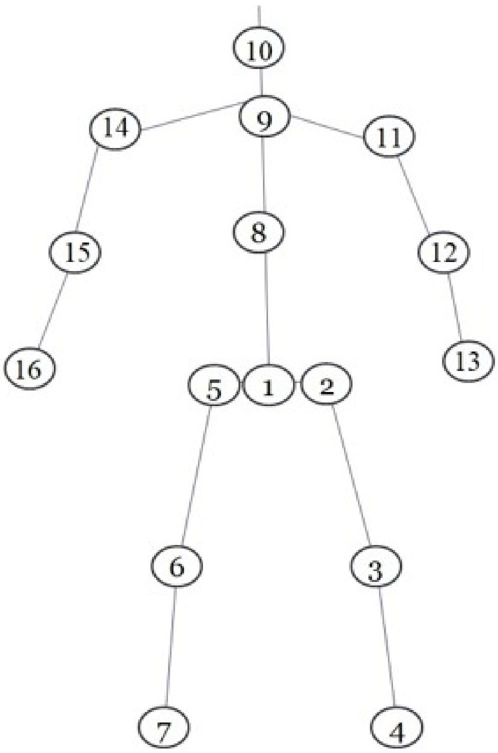
The analysis of the Ground Reaction Force (GRF) on each foot is essential for a correct analysis of the interaction forces of the body with the ground. During the run, only one foot is in contact with the ground, which facilitates the measurement of GRF in each foot. However, in the walk there is an interval whose two feet are simultaneously in contact with the ground and, consequently, making it difficult to analyze the individual GRF in each foot. One solution to this issue is to analyze the GRF in two independent force plate positioned posterior and anterior under the mat.

2.1 Experimental data collection

One healthy volunteer (one men, 31 years old, 76 kg, and 1.82 m) with no previous history of musculoskeletal injury participated in the test. The volunteer was individually instructed to walk on a treadmill with a controlled speed of “natural” speed, where the kinetic and kinematic data were recorded simultaneously. The project was approved by the research ethics committee, protocol number 3.006.449.

2.2 Kinect data treatment

Based on the coordinates of the points captured by the Kinect sensor, it is possible to determine the relative movement of each segment in relation to its predecessor within a hierarchical chain. The kinematic chain starts in the Pelvis (segment 1) and follows the branch to the extremities: right ankle (4); left ankle (7), neck (10), right wrist (13) and left wrist (16). The other joints were disregarded as they are not relevant to the analysis of the human path.



Number	Description
1	Pelvis
2	Hips_Right
3	Knee_Right
4	Ankle_Right
5	Hips_Left
6	Knee_Left
7	Ankle_Left
8	Spine
9	Clavicle
10	Neck
11	Shoulder_Right
12	Elbow_Right
13	Wrist_Right
14	Shoulder_Left
15	Elbow_Left
16	Wrist_Left

Figure 2. Kinematic chain hierarchy

The Kinect has one color camera and one depth sensor, in addition to the stereoscopic 3D vision device. For each pixel in the color image, it ultimately provides 4 pieces of information: 3 of color components and 1 of depth (except at the edges of the image). The Kinect then calculates the average distance between its position and each of the pixels in the image (ignoring the pixels for which there are no depth measurement). The calculation of the average distance is carried out in two steps. First, the projected coordinates (column, row, depth) of each pixel are converted into square coordinates. The Cartesian system has its origin at the Kinect with the X axis pointing towards its right, the Y axis up and the Z axis forward. After converting the pixels to Cartesian coordinates, the program calculates the Euclidean distance of each pixel at the origin (Microsoft, 2021).

The data were collected at a 30 fps (frames per second) rate. A cubic interpolation was done in the data through a filter lower than 6 hz.

The joint angles and relative movement of flexion-extension (α) around x, adduction/abduction (β) around y, and internal and external rotation (γ) around z, of the body segments, are determined using the method. Euler/Cardan angle (Eq. (1), where 'c' is cosine and 's' sine), with XYZ elementary rotation.

$$R_A(\alpha,\beta,\gamma) = \begin{bmatrix} c(\gamma)c(\beta) & -s(\gamma)c(\alpha) + c(\gamma)s(\beta)s(\alpha) & s(\gamma)s(\alpha) + c(\gamma)s(\beta)c(\alpha) \\ s(\gamma)c(\beta) & c(\gamma)c(\alpha) + s(\gamma)s(\beta)s(\alpha) & -c(\gamma)s(\alpha) + s(\gamma)s(\beta)c(\alpha) \\ -s(\beta) & c(\beta)s(\alpha) & c(\beta)c(\alpha) \end{bmatrix} \quad (1)$$

The generated data were treated and presented in graphic form to facilitate the analysis.

2.3 Force plate data treatment

Force plates (also known as force platforms, strength plates, strength platforms, and in technical terms as force transductors) are mechanical force sensor that do not need to be embedded on the subject. These systems are composed of a simple pressure plate, divided into load cells, placed on the walking path. They are designed to measure the effort and moments that apply to its top surface while a subject stand, mount or jump on it. The treadmill was instrumented with 2 square force platforms, composed of 4 load cells of the CZA/ZL-200 type at each vertex as shown in Figure 3. An HBMI amplifier and converter was used.

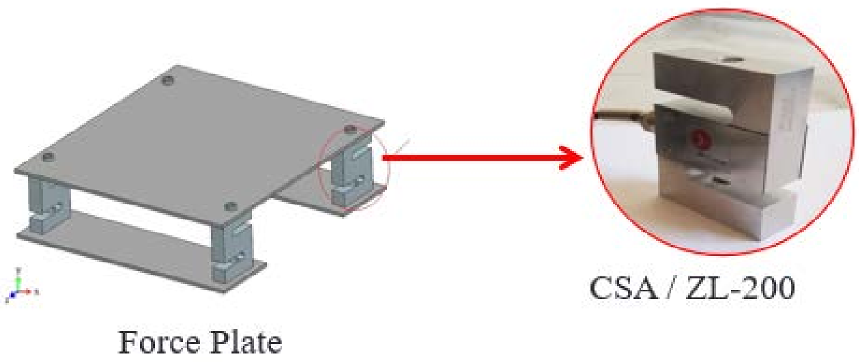


Figure 3. Representation of the Force Platform and the positioning of CSA/ZL-200 load cells.

The force plates located under the belts record the ground reaction forces components (Fx, Fy and Fz) and their moments (Mx, My and Mz) generated by the subject. High-performance motor controls and on-board software provides the clinical staff with an intuitive interface for controlling the pitch and roll of the treadmill, the direction of travel of the belts and the belt speed.

It was kept in mind the effects of sampling error due to the circuitry acquiring the force plates signals not being properly and symmetrically constructed that could lead to two or more different frequencies in the signals (Rahman, 2019).

Initially, an initial calibration of the platforms will be carried out, with the static positioning of the individual under each force platform according to the collection of weight and the individual and tare of the platforms. Thereafter, the patient will walk and run during the period established by the clinical staff. The GRF values will be correlated in percentage with the subject’s weight.

3. RESULTS

Initially, the individual was captured with point clouds in flight mode, as shown in Figure 4, for calibration and preliminary acquisition of anthropometric data. Calibration of load cells and force platforms was also performed, according to the individual's weight (76kgf).

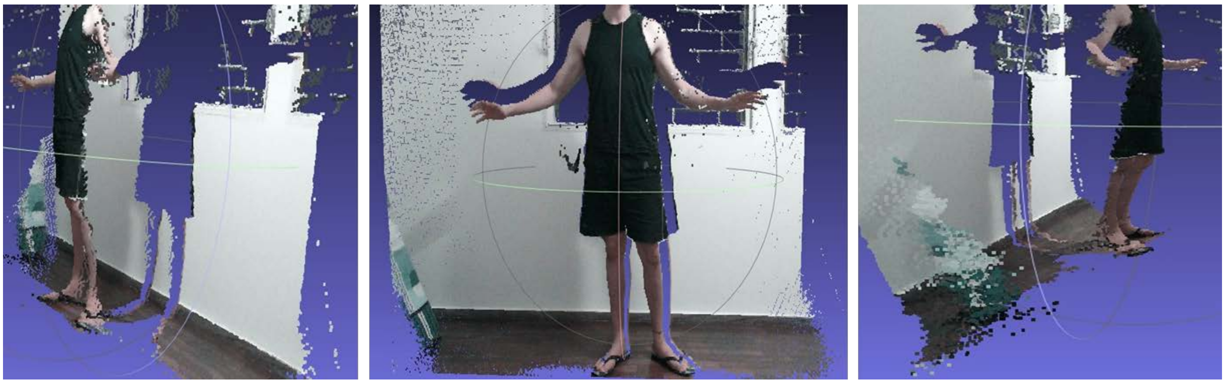


Figure 4. Body reconstruction using point clouds.

The individual was then instructed to walk on the treadmill, with controlled speed adjusting to their natural walking speed of approximately 4 km/h, for approximately 5 minutes, to adjust for walking on the treadmill. The position data of each joint were mapped using Kinect One, with acquisition rate of 30fps, as shown in Figure 5 a).

a) b)

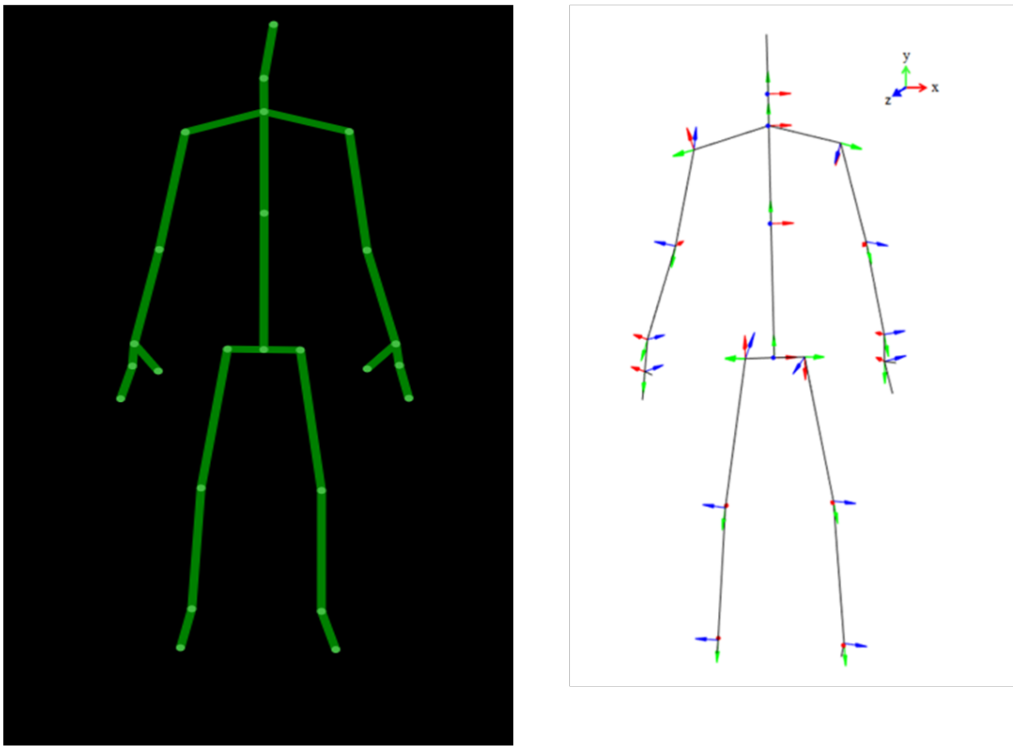


Figure 5. Mapping the joints of the human body. a) Identification of joints and acquisition of position; b) Reconstruction of body segments and representation of the joint coordinate system.

From the position of the human joints, the coordinate systems of each joint were traced, and the segments were reconstructed for a 3D representation of the entire walk, as shown in Figure 5 b). The flexion/extension movement (relative movement of the joints in the direction of greater magnitude of movement, rotation around x) was also graphically presented using the Euler Angles method as shown in Figure 5. Data were filtered and processed in Matlab, using linear interpolation and an FFT filter. The data represented in Figure 6 follow the same pattern presented in Literature. (Nordin and Frankel, 2001 and Neumann, 2011).

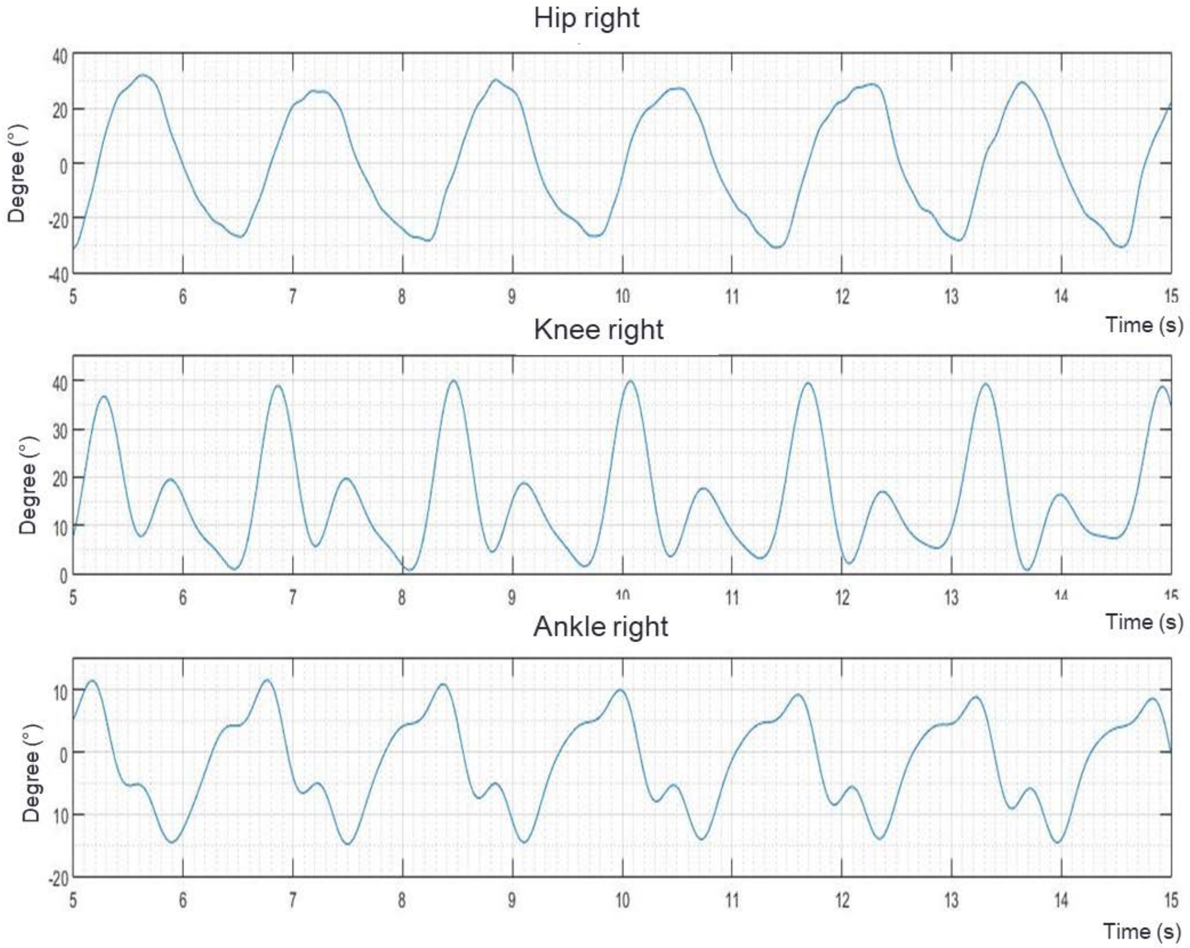


Figure 6: Representation of the flexion and extension angles of the hip, knee, and ankle in continuous walking under the treadmill.

The GRF data of the volunteer's right foot (76 kg), in the vertical direction, collected by the force platforms, in two walking cycles, treated with the Catman Easy software, are shown in Figure 7. The initial contact peak is observed. with a value higher than body weight, representing the initial contact of the foot to the ground, followed by an impulsion peak, the same pattern portrayed in the literature (Barela, 2011).

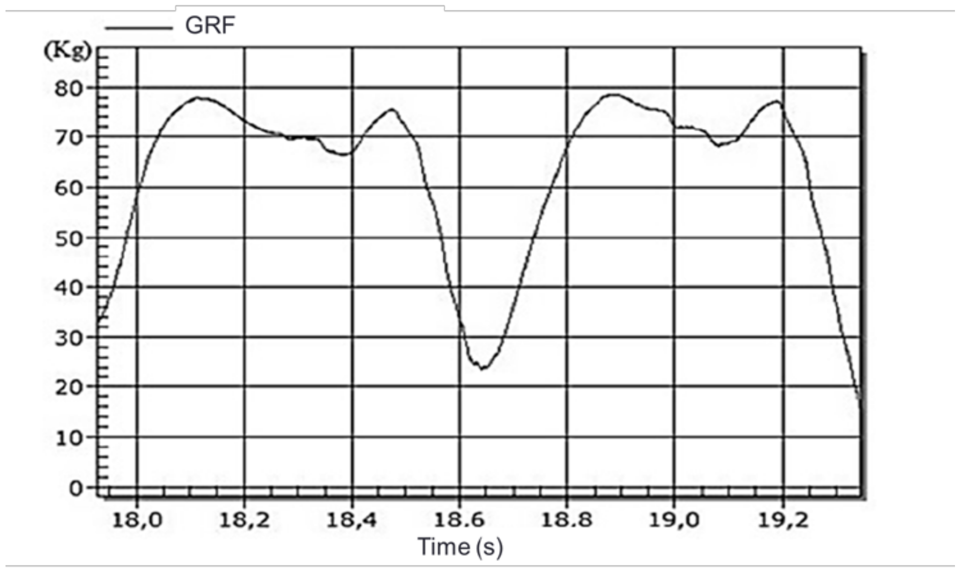


Figure 7: Vertical GRF of the right foot for walking on a treadmill for a volunteer (76Kg).

4. CONCLUSION

This method creates an in-depth assessment of human gait by combining a functional treadmill instrumented with a force plate and Kinect one sensor. It is a quick and efficient assessment process because the environment of a treadmill provides a walking challenge that demands the patient apply its personal gait on a constant pattern.

As it shows in Figure 6, a human gait follows a pattern, each pace, each step is a repeat of the previous one and the same as the following. And so, a person walk can be analyzed by software, and compared to a standard, therefore allowing a medical professional to assess any irregularities or problems that a specific patient may have. With the correct analysis, the patient can receive the correct treatment to repair or restore its gait, fixing issues that could have led to a lack of balance, spine and hips pain, and other physical deficiencies that can be caused by an unhealthy gait during walking.

The data presented follow the pattern presented in Literature. Measurements of specific groups of volunteers and a comparison with the standard system must be performed to validate the developed systems.

5. ACKNOWLEDGMENTS

The authors are grateful for the funding of the project by PUCMinas, and by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001.

6. REFERENCES

Adikari, S., Ganegoda, N., and Wanniarachchi, W. K., 2017. “Non-Contact Human Body Parameter Measurement Based on Kinect Sensor”. *IOSR Journal of Computer Engineering*. Vol. 19, pp. 2278-661.

Auvinet, E., Multon, F., Manning, V., Meunier, J., and Cobb, J., 2017. “Validity and sensitivity of the longitudinal asymmetry index to detect gait asymmetry using Microsoft Kinect data”. *Gait & posture*, Elsevier. Vol. 51, pp. 162–168.

Barela, A., 2011. “Utilização da plataforma de força para aquisição de dados cinéticos durante a marcha humana”. *Brazilian Journal of Motor Behavior*. Vol. 6, pp. 56–61.

Caparelli, T. B., and Naves, E. L. M., 2017. “Reconstruction of gait biomechanical parameters using cyclograms and artificial neural networks”. *Research on Biomedical Engineering*, SciELO Brasil. Vol. 33, n. 3, pp. 229–236.

Capozzo, A., 1984. “Gait analysis methodology”. *Human Movement Science*. Vol.3, pp. 27-50.

Dolatabadi, E., Taati, B., and Mihailidis, A., 2016. “Concurrent validity of the Microsoft Kinect for windows v2 for measuring spatiotemporal gait parameters”. *Medical engineering & physics*, Elsevier. Vol. 38, n. 9, pp. 952–958.

Dubois, A. and Bresciani, J.-P., 2018. “Validation of an ambient system for the measurement of gait parameters”. *Journal of biomechanics*, Elsevier. Vol. 69, pp. 175–180.

Edginton, K. A., Güler, H. C., Ober, J. J., and Berme, N., 2007. “Instrumented treadmills: Reducing the need for gait labs”. *CMBES Proceedings*. Vol. 30.

Eltoukhy, M., Oh, J., Kuenze, C., and Signorile, J., 2017. “Improved Kinect-based spatiotemporal and kinematic treadmill gait assessment”. *Gait & posture*, Elsevier. Vol. 51, pp.77–83.

Forner-Cordero, A., Koopman, H., and Helm, F. Van der., 2006. “Inverse dynamics calculations during gait with restricted ground reaction force information from pressure insoles”. *Gait & posture*, Elsevier. Vol. 23, n. 2, pp. 189–199.

Hong, C.-Y., Guo, L.-Y., Song, R., Nagurka, M. L., Sung, J.-L., and Yen, C.-W., 2017. “Developing a low-cost force treadmill via dynamic modeling”. *Journal of healthcare engineering*, Hindawi. Vol. 2017.

Hulle, R. V., Schwartz, C., Denoël, V., Croisier, J.-L., Forthomme, B., and Brüls, O., 2020. “A foot/ground contact model for biomechanical inverse dynamics analysis”. *Journal of Biomechanics*, Elsevier. Vol. 100, p. 109412.

Liao, Y., Vakanski, A., Xian, M., and Paul, D. R., 2020. “A review of computational approaches for evaluation of rehabilitation exercises”. *Computers in Biology and Medicine*, p. 103687.

Macpherson, T. W., Taylor, J., Mcbain, T., Weston, M., and Spears, I. R., 2016. “Real-time measurement of pelvis and trunk kinematics during treadmill locomotion using a low-cost depth-sensing camera: A concurrent validity study”. *Journal of biomechanic*s, Elsevier. Vol. 49, n. 3, pp. 474–478.

Martins, J. S. R., Braga, E. G. E. R., Abdala, L. M., Sapori, M. H. C., Machado, G. M. C., Vimieiro, C. B. S., 2019. “Development of motion capture system prototype for gait test”. In: *25th ABCM International Congress of Mechanical Engineering - COBEM-2019*, Uberlândia. Proceedings of COBEM-2019.

Martins, J. S. R., Meyer, I. Z. L., Nascimento, D. H. A., Menin, I. S. D., Sabino, G., Vieira, W. L., Gomes, N. A., Vimieiro, C. B. S., 2021. “Accessible Technologies for Kinetic and Kinematic Analysis of people with disabilities: A Literature Review”. *Brazilian Journal of Development*, 2021. Vol.7, n.5, pp.44529-44541.

Microsoft. Azure Kinect DK hardware specifications. Available in: https://docs.microsoft.com/en-us/azure/kinect-dk/hardware-specification. Accessed in April 2021.

Müller, B., Ilg, W., Giese, M. A., and Ludolph, N., 2017. “Validation of enhanced Kinect sensor based motion capturing for gait assessment”. *PloS one*, Public Library of Science. Vol. 12, n. 4, p. e0175813.

Nordin, M. and Frankel, V.H., 2001. *Basic biomechanics of the musculoskeletal system*. Lippincott Williams & Wilkins, 1st Edition.

Neumann, D.A., 2011. *Kinesiology of the musculoskeletal system: foundations for rehabilitation*. Elsevier Health Sciences, 2rd Edition.

Perry, J. and Schoneberger, B., 1992. *Gait Analysis: Normal and Pathological Function: SLACK*.

Rahman, M. M., 2019. "Critical Analysis of Sampling and Non-Sampling Error". Available in: https://www.researchgate.net/publication/334277011_Critical_Analysis_of_Sampling_and_Non-Sampling_Error. Accessed in August 2021.

Rose, J. and Gamble, J. G., 2007. *Gait: theory and practice of human locomotion* (in Portuguese). [S.l.]: Rio de Janeiro: Editora Guanabara Koogan.

Silva, M., Shepherd, E. F., Jackson, W. O., Dorey, F. J., and Schmalzried, T. P., 2002. "Average patient walking activity approaches 2 million cycles per year: pedometers under-record walking activity". *The Journal of Arthroplasty*. Vol 17, n. 6, pp. 693–697.

Springer, S., and Yogev, S., 2016. "Validity of the Kinect for gait assessment: A focused review". *Sensors*, Multidisciplinary Digital Publishing Institute. Vol. 16, n. 2, p. 194.

Tan, D., Pua, Y.-H., Balakrishnan, S., Scully, A., Bower, K. J., Prakash, K. M., Tan, E.-K., Chew, J.-S., Poh, E., and Tan, S.-B. et al., 2019. "Automated analysis of gait and modified timed up and go using the Microsoft Kinect in people with Parkinson's disease: associations with physical outcome measures". *Medical & biological engineering & computing*, Springer. Vol. 57, n. 2, pp. 369–377.

Tanaka, R., Takimoto, H., Yamasaki, T., and Higashi, A., 2018. "Validity of time series kinematical data as measured by a markerless motion capture system on a flatland for gait assessment". *Journal of biomechanics*, Elsevier. Vol. 71, pp. 281–285.

Tinetti, M. E., Liu, W.-L., and Claus, E. B., 1993. "Predictors and prognosis of inability to get up after falls among elderly persons". *Journal of the American Medical Association* (Jama). Vol 269, n. 1, pp. 65–70.

Vimieiro, C., Andrada, E., Witte, H., and Pinotti, M., 2015. "A computational model for dynamic analysis of the human gait". *Computer methods in biomechanics and biomedical engineering*, Taylor & Francis. Vol. 18, n. 7, pp. 799–804.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.