Physical Modelling of Normal and Pathological Gait Using Identification of Kinematic Parameters

C. A. Collazos and R. E. Argothy

Abstract—This paper presents the one-dimensional gait kinematic principle, in order to identify the kinematic parameters for normal and pathological (transtibial amputation) gait of two subjects with similar anthropometry. Each type of gait is associated with uniform linear motion and uniformly accelerated motion. We used the Manuela Beltrán University Biomechanics Laboratory. The developed physical model complements the information of the data acquisition system and is used for biomechanics modelling.

Keywords—Gait, kinematic, modelling, physics, prosthesis.

I. INTRODUCTION

THE gait analysis is the measurement and assessment of human locomotion which includes both walking and running [1]. These movements, known as stereotyped reflexes, are characterized by being repetitive in time when the velocity and the acceleration are normal [2]. Therefore, it is possible to obtain reference curves during each movement phase that could help determine abnormal patterns or pathologies, which are related to the musculoskeletal system and modify normal behavior [3].

The different tissues involved during walking, namely: muscles, tendons, cartilage, ligaments, connective tissue (fascia) and the bone component, perform different functions, such as: motion generation, power transmission, buffer loading and joint stabilization of segments, among others. These functions are the basis of motion and, hence, are constantly analyzed and evaluated to determine alterations that modify their performance [4], [5].

In particular, subjects with lower limb amputations have compensatory adjustments in gait, where the soft tissues and the mechanical stress must adjust to the structural and functional changes of the body. This suggests an increased muscular demand, energy expenditure, the alignment of gravity center and mass center, the static and dynamic postural alignment, among others. These parameters are relevant for measuring the risk factors presented by these subjects, which include falling due to alterations in the stability and balance control of the body [6] [7],[8].

The aim of this work is to compare the gait analysis of one healthy subject and one pathological subject. In this research, "pathological gait" particularly refers to prosthetic gait transtibial amputation. The motion analysis techniques used to measure accurately kinematic curves are obtained through skin passive markers, which allow recording of position, velocity and acceleration of a body segment. These measurements provide quantitative information about the movement [9].

A complete review of human walking modelling and simulation is presented in [10], [11], [12], [13]. This research review focuses on physics-based human walking simulations in biomechanics literature and robotics. The gait synthesis methods are broadly divided into five types: inverted pendulum model; passive dynamics walking; zero-moment point methods; optimization-based methods; and control-based methods [11],

This paper describes the behavior of the normal and pathological gait at a normal velocity and acceleration. We identify the kinematic parameters for each type of gait and compare the kinematics curves presented in each of the cases.

The article is structured as follows: Section II shows the used instrumentation and the associated markers for gait evaluation. Section III presents the identification of the kinematic parameters related to the gait and the mathematical tools. Finally, section IV is dedicated to conclusions.

II. INSTRUMENTATION

The Biomechanics Laboratory of the Manuela Beltrán University was used for data logging. We used BTS GAITLAB [14]. This acquisition system of high precision for motion analysis has six optoelectronic cameras, that measure the displacement ($\pm 10^{-7} m$) of body segments in time ($\pm 10^{-2} s$).

The system requires 3 passive markers placed strategically on the subjects. Fig. 1 indicates the location of the markers in posterior and anterior views. The markers involved in the gait were the sacrum (marker 6), only visible in the posterior view, the right greater trochanter (marker 7) and the left greater trochanter (marker 8). The study of movement in this work was restricted only to forward movement, which was assigned to the X axis, in the laboratory reference system.

C. A. Collazos is with the Physics Laboratory in Manuela Beltrán University, Avenida Circunvalar No. 60-00, Bogotá, Colombia (e-mail: carlos.collazos@docentes.umb.edu.co).

R. E. Argothy is with the Biomechanics Laboratory in Manuela Beltrán University, Avenida Circunvalar No. 60-00, Bogotá, Colombia (e-mail: rodrigo.argothy@docentes.umb.edu.co).

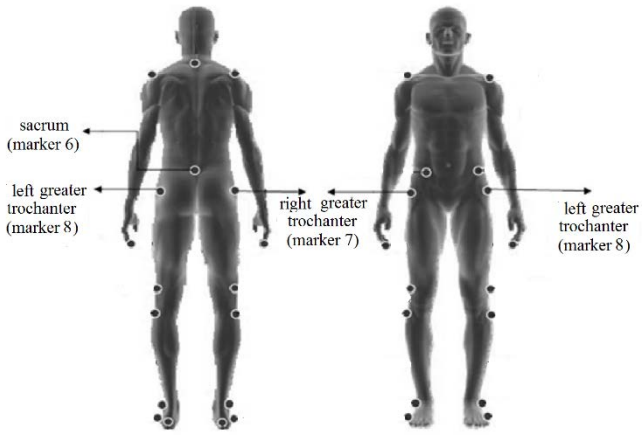

Fig. 1. Disposition of the cutaneous passive markers in the human body [14]

III. METHOD, RESULTS AND ANALYSIS

We use the physics fundamentals of one-dimensional kinematics. For the data analysis, the least squares and correlation coefficient methods were used [15]. The test was applied for two male subjects of 34 ($\pm$ 1) years of age, 1.64 ($\pm$ 0.01) m of height and a body mass of 64 ($\pm$ 0.1) kg. One of the subjects has unilateral transtibial amputation of right lower extremity. The other subject is healthy, has normal gait and an anthropometry similar to that of the pathological subject. The study was approved by the Ethics Committee of the Manuela Beltrán University. Written informed consent was obtained from the subjects.

The figures 2 to 6 show experimental data in dotted lines and models in continuous black lines. The bigger dots represent normal gait and smaller dots depict pathological gait. The units for all variables and parameters use International Units System.

A. Normal and Pathological Gait with constant velocity

Fig. 2 illustrates the trajectories for normal and pathological gait. This figure indicates the position register of the sacrum (marker 6) and the linear interpolation of the two trajectories. Here, it is observed that there is a high correlation between the model and the experimental data for normal gait. This correlation is statistically significant ($r = 0.997$). The identification of the model allows determining the initial position (x_0 =-2.13m) and the average velocity on the walk (v_0 =1.00m/s). Therefore, the model of the position in function of time for normal gait is $x(t) = -2.13 + 1.00t$. Also, we observed that there is a high correlation between the model and the experimental data for pathological gait. This correlation is statistically significant ($r = 0.997$). The identification of the model allows determining the initial position (x_0 =-2.12m) and the average velocity on the walk (v_0 =0.60m/s). Therefore, the model of the position in function of time for pathological gait is $x(t) = -2.12 + 0.60t$. We used the relative error, defined as: $\%E = \left[\frac{control - tested}{control}\right].100\%$, to compare the average velocity of normal gait (control value) and pathological gait (tested value). In this case we obtained a relative error of $\%E$ =39.60%.

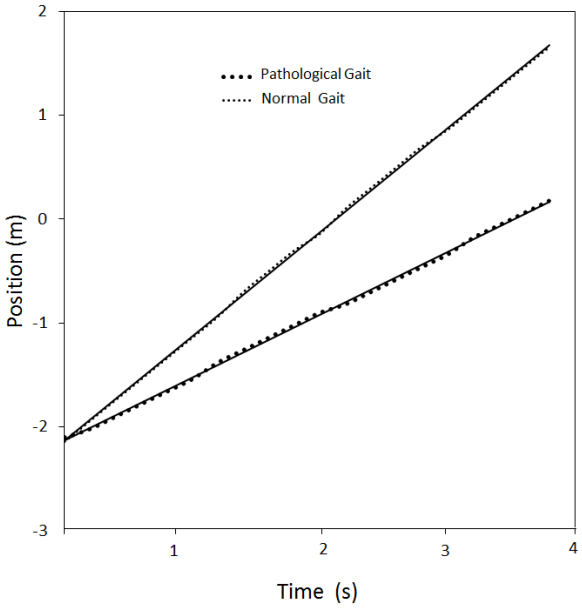

Fig. 2 The position–time graph on the X axis for the sacrum with constant velocity.

Fig. 3 shows the position registered of the right greater trochanter (marker 7) and the linear interpolation for normal and pathological gait. The identification of the model for normal gait determined the initial position (x_0 =-213m) and the average velocity (v_0 = 1.02 m/s). Here, it can be seen that there is a high correlation between the position and the experimental measurements with $r = 0.996$. The model of the position in function of time for normal gait is, therefore, $x(t) = -2.13 + 1.02t$. The identification of the model for pathological gait determined the initial position (x_0 =-2.12m) and the average velocity (v_0 = 0.61 m/s). Here, it can be seen that there is a high correlation between the position and the experimental measurements with $r = 0.996$. The model of the position in function of time for pathological gait is, therefore, $x(t) = -2.12 + 0.61t$. In this case, we obtained a relative error of $\%E$ =39.60% for average velocity.

Fig. 4 indicates the position register of the left greater trochanter (marker 8) and the linear interpolation for normal and pathological gait. The identification of the model for normal gait determined the initial position (x_0 =-2.13m) and

the average velocity (v_0=0.99 m/s). In this case, the correlation coefficient is $r = 0.996$. Consequently, the model of the position in function of time for normal gait is $x(t) = -2.13 + 0.99t$. The identification of the model for pathological gait determined the initial position (x_0=-2.12m) and the average velocity (v_0=0.59 m/s). In this case, the correlation coefficient is $r = 0.996$.The model of the position in function of time for pathological gait is, consequently, $x(t) = -2.12 + 0.59t$. In this case, we obtained a relative error of $\%E$=40.00% for average velocity.

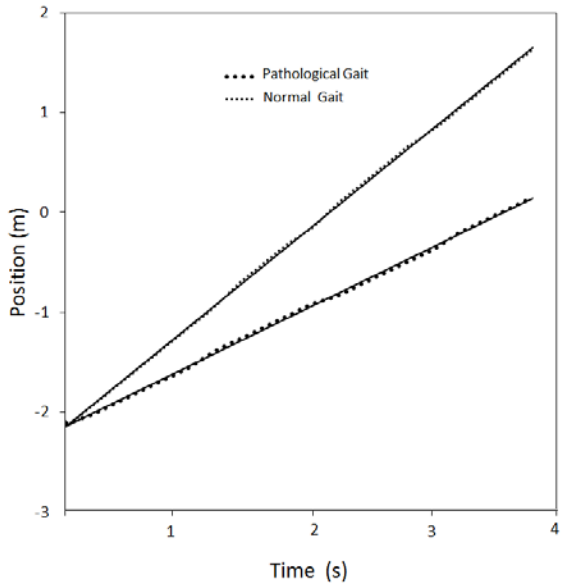

Fig. 3 The position–time graph on the X axis for the right greater trochanter with constant velocity

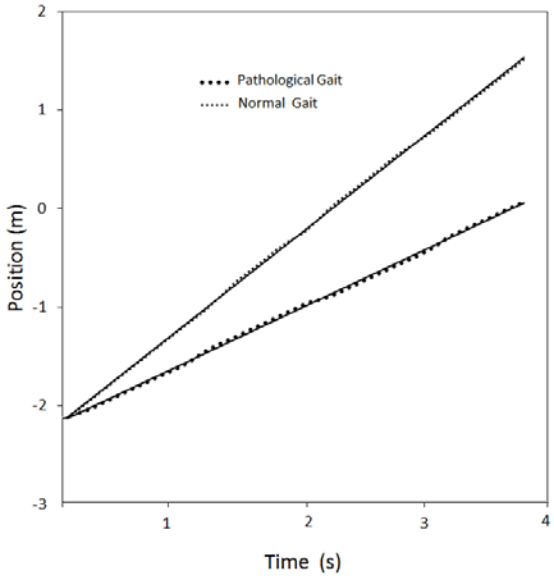

Fig. 4 The position–time graph on the X axis for the left greater trochanter with constant velocity

Based on physics' models found for the sacrum, for the right and left greater trochanter, our experimental data support the model reasonably well. We observed a 0.99 higher correlation between the kinematics position models and the obtained measurements, which meets the characteristics of a uniform linear motion according to [15]. We found significant differences between the average velocity of the normal and pathological gait in the three markers. The velocity relative error $\%E$ is around of 39% for the sacrum, the right and left greater trochanter.

B. Normal and Pathological Gait with constant acceleration

Fig. 5 illustrates the trajectories for normal and pathological gait. This figure indicates the position registered of the sacrum (marker 6) and quadratic interpolation of the two trajectories. The identification of the model allows determining the initial position (x_0=-2.13 m), initial velocity (v_0=-1.09 m/s) and half the average acceleration (0.90 m/s^2) for normal gait. There is a high correlation between the model and the experimental data ($r = 0.997$). The model of the position in function of time for normal gait, consequently, is $x(t) = -2.13 - 1.09t + 0.90t^2$. The identification of the model for pathological gait determines the initial position (x_0 =-2.27 m), initial velocity (v_0=-0.31m/s) and half the average acceleration (0.29 m/s^2). There is a high correlation between the model and the experimental data ($r = 0.997$). The model of the position in function of time for pathological gait, consequently, is $x(t) = -2.27 - 0.31t + 0.29t^2$. In this case, we obtain a relative error for average acceleration of $\%E$ =71% and of $\%E$ =67% in initial velocity.

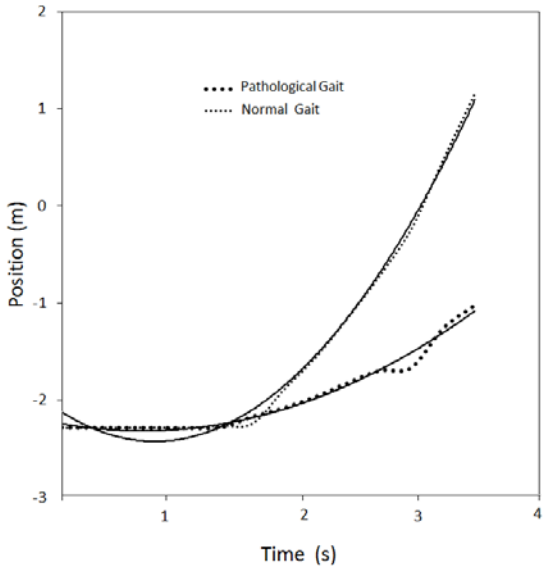

Fig. 5 The position-time graph on the X axis for the sacrum with constant acceleration

Fig. 6 indicates the position registered of the right greater trochanter (marker 7) and the quadratic interpolation for normal and pathological gait. The identification of the model for normal gait allows determining the initial position (x_0 =-2.10m), initial velocity (v_0 =1.18 m/s) and half the average acceleration (0.91 m/s^2). There is a high correlation between the position and the experimental measurements ($r = 0.996$). Hence, the model of the position in function of time for normal gait is $x(t) = -2.10 - 1.18t + 0.91t^2$. The identification of the model for pathological gait determines the initial position (x_0 =-2.27 m), initial velocity (v_0 =-0.33 m/s) and half the average acceleration (0.31 m/s^2). There is a high correlation between the model and the experimental data ($r = 0.997$). Consequently, the model of the position in function of time for pathological gait is $x(t) = -2.27 - 0.33t + 0.31t^2$. We obtain a relative error for average acceleration of $\%E$ =72% and of $\%E$ =65% for initial velocity.

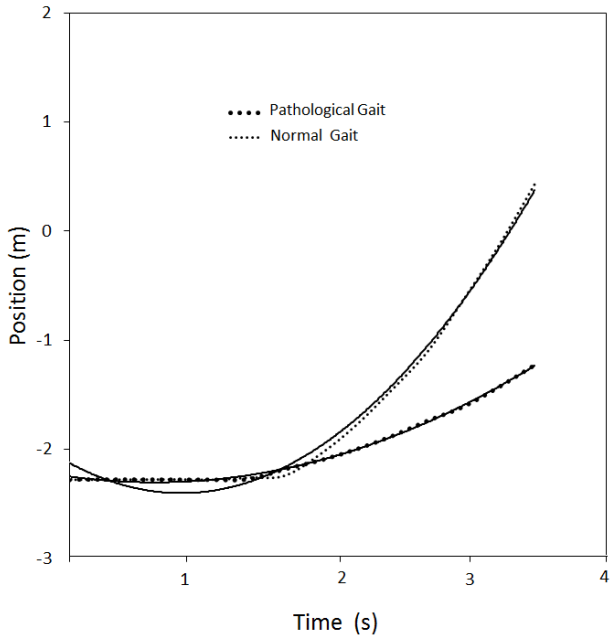

Fig. 6 The position-time graph on the X axis for the right greater trochanter with constant acceleration

Fig. 7 indicates the position register of the left greater trochanter (marker 8) and the quadratic interpolation for normal and pathological gait. The identification of the model for normal gait allows determining the initial position (x_0 =-2.15m), initial velocity (v_0 =1.06 m/s) and half the average acceleration (0.89 m/s^2) for normal gait. There is a high correlation between the model and the experimental data ($r = 0.997$). The model of the position in function of time for normal gait is $x(t) = -2.15 - 1.06t + 0.89t^2$.

The identification of the model for pathological gait determines the initial position (x_0 =-2.27 m), initial velocity (v_0 =-0.30 m/s) and half the average acceleration (0.29 m/s^2). There is a high correlation between the model and the experimental data ($r = 0.997$). Consequently, the model of the position in function of time for pathological gait is $x(t) = -2.27 - 0.30t + 0.29t^2$. In this case, the relative error for average acceleration is $\%E$ =70% and $\%E$ =67% for initial velocity.

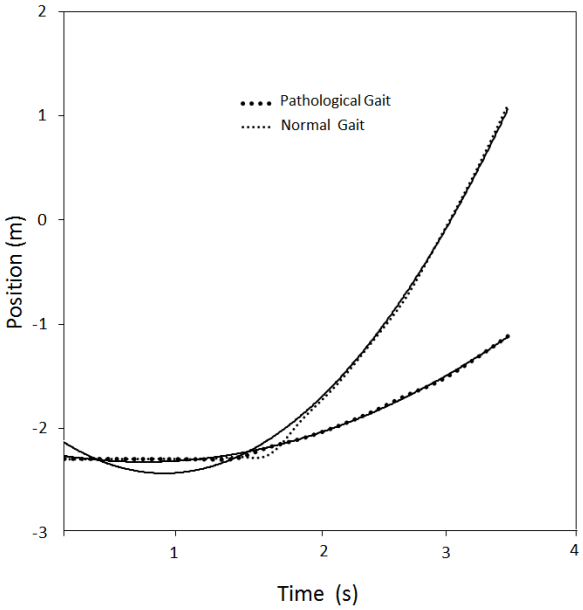

Fig. 7 The position-time graph on the X axis for the left greater trochanter with constant acceleration

According to kinematics curves and mathematical models found for the sacrum, for the right and left greater trochanter, we observed a 0.99 higher correlation between the kinematic position models and the experimental measurements, which meets the characteristics of a movement with constant acceleration regard to [15]. We found significant differences between the parameters of normal and pathological gait in the three markers. The relative error $\%E$ for initial velocity is around of 69% for the sacrum, for the right and left greater trochanter. The relative error $\%E$ for average acceleration is around of 70% for the three markers.

IV. CONCLUSION

This work has presented a comparison of a simple model of normal and pathological gait for a subject with unilateral transtibial amputation. Experimental results were validated for the physics models and parameters were found. The technique used involves three reference markers (sacrum, right and left greater trochanter) related to the center of mass of the human body. The identified models predict in time quantities such as position, velocity and acceleration, at the different types of motion with normal velocity and constant acceleration. The

orders of magnitude found for the physics position models are within the range of magnitudes reported by authors like Winter in [9].

This work compares physics models between normal and pathological gait. Due to the fact that the normal gait may be affected in subjects with unilateral transtibial lower limb amputation, the compensation in pelvic floor and lower limbs are notorious in gait of people with amputation as visible in the graphics of trajectory. In this sense, our purpose in the future is to establish a three-dimensional kinematic modelling involving other joints such as hip, knee and ankle, depending on the level of amputation, for determining characteristic patterns in each study subject.

It is important to note that the normal gait pattern modelling can be affected by many causes, such as height, age, footwear, terrain, load, activity of the subject, which are not necessarily pathological but are related to the alteration or adaptation of musculoskeletal structures for movement. In this case, we can propose, in the future, studies to do comparisons of the gait in different pathologies and define patterns for each pathology.

REFERENCES

[1] K. Luttgens, K. Wells, *Bases científicas del movimiento humano*. Madrid, 1982, pp. 21–34.

[2] K. Hainaut, *Introducción a la Biomecánica*, Barcelona, 1982, pp. 31–34.

[3] B. Le Veau. *Biomecánica del movimiento humano*. México, 1991. pp.51–54.

[4] F. Plas, E. Viel, Y. Blanc. *La marcha humana. Cinesiología dinámica, biomecánica y patomecánica*. Barcelona, 1984, pp.12–24

[5] P. Rasch, R. Burke, *Kinesiología y Anatomía aplicada*, Buenos Aires, 1986, pp.25–27.

[6] Natalie Vanicek , Siobhan Strike , Lars McNaughton, Remco Polman. Gait patterns in transtibial amputee fallers vs. non-fallers: Biomechanical differences during level walking , UK, 2009 pp.415–420.

[7] Ava D. Segal, Michael S. Orendurff, Joseph M. Czerniecki ,Jason Schoen, Glenn K. Klute. Comparison of transtibial amputee and non-amputee biomechanics during common turning task. USA, 2011,pp. 41–47.

[8] Yoshimasa Sagawa Jr et al. Biomechanics and physiological parameters during gait in lower-limb amputees: A systematic review. France, 2011 pp. 511–526

[9] D. Winter, *Biomechanics of Human Movement*, USA, 1979, pp.9–22.

[10] Y. Xiang , JS Arora ,K. Abdel-Malek, *Physics-based modeling and simulation of human walking: a review of optimization-based and other approaches*, Struct Multidisc Optim 42, 2010,pp 1-23.

[11] C. Detrembleur , F. Dierick F, A. van den Hecke A, *Motion of the body centre of gravity as a summary indicator of the mechanics of human pathological gait*, Gait Posture 12(3),2010,,pp. 243-250.

[12] Y. Kalyan Chakravarthy, et al, *Haptics based Robotic Prosthetic Leg*, Advances in Robotics , Mechatronics and Circuits, Proceedings of the 18th International Conference on Circuits (part of CSCC '14), Santorini Island, Greece, July 18-20, 2014,pp 296-302.

[13] Nurfarahin Onn, et al, *Considerations of Biped Locomotion for Lower Limb Exoskeleton Designs*, Latest Trends in Circuits, Control and Signal Processing, Proceedings of the 13th International Conference on Robotics,Control and Manufacturing Technology (ROCOM '13), Kuala Lumpur, Malaysia ,April 2-4, 2013, pp. 59-64.

[14] BTS Gait-Lab, www.btsbioengineering.com/

[15] C. A. Collazos y R. E Argothy , *A physical model for teaching one-dimensional kinematic gait*, Advances in Educational Technologies, Proceedings of the 2014 International Conference on Education and Modern Educational Technologies (EMET 2014), Santorini Island, Greece, July 18-20, 2014,pp 88-92.