A 3D PHYSICS-BASED MODEL TO SIMULATE NORMAL AND PATHOLOGICAL GAIT PATTERNS

Christian Cifuentes, Fabio Martínez and Eduardo Romero
BioIngenium Research Group, Universidad Nacional de Colombia, Bogotá, Colombia

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Abstract: This article presents a novel 3D physics-based human gait model that allows to quantify and simulate the dynamic patterns of normal and pathological movements in the sagittal and coronal views, using an enhanced inverted pendulum approach. The method outperforms the classic planar representations that do not consider important gait phases like the double stance phase and the heelstrike, crucial in proper gait descriptions on clinical routine. The model was assessed by simulating gait cycles and comparing the obtained trajectories with actual normal and pathological gait data. Results showed that the normal and pathological kinematic patterns generated by our model are highly similar to the actual data, obtaining an accuracy of about 87%.

1 INTRODUCTION

The gait is one of the most broadly studied motion in very different domains such as medicine, animation or robotic (Xiang et al., 2010). This movement is the result of complex interactions between several sub-systems, which work together to generate the body dynamics that underlies the bipedal displacement (Gage, 2004). This human gait patterns are frequently disturbed in many types of pathologies. In the clinical routine, a physician or rehabilitation expert searches pathological gait patterns (according to her/his expertise), supporting the decision on some statistical tests of the acquired data and introducing thereby an inevitable expert-dependent bias (Delp et al., 2007).

In addition, traditional methodologies to capture gait patterns are very invasive and alter the natural gait gestures which also are contaminated by capture noise. Therefore, development of gait models achieving an accurate quantitative movement description has become a priority to support the physician decisions (Fregly, 2008; Kuo and Donelan, 2010).

This work introduces a novel 3D human gait model that generates the dynamic gait patterns in the sagittal and coronal views observed in a clinical gait analysis using a physics-based approach . It provides high flexibility, generating a large number of walking patterns using only a complete CoG trajectory representation and the heel trajectory data obtaining normal and pathological gait patterns, for instance the dynamics of a typical cerebral palsy gait (Crouch gait), changing a few set of parameters. This simple mechanic gait representation simulates the energy accumulation of different anatomical elements, responsible for most non linear gait patterns: it uses a double-inverted pendulum system to simulate the single stance CoG trajectory, while the double stance CoG trajectory is simulated by a double spring-mass system, in both sagittal and coronal views. The obtained trajectory feeds a human like-structure, which is animated using a learned heel trajectory and a classical inverse kinematic to calculate the dynamic patterns. The rest of the paper is organized as follows: Section Related Works review similar approaches related with the model of human gait, section Materials and Methods introduces our model, section Results demostrates the effectiveness of the model. The last section presents the conclusion and future works.

2 RELATED WORKS

Several models have been previously proposed for simulating the human gait, among which the physics-based models obtain realistics and natural representations of the human Center of Gravity (CoG).(Xiang et al., 2010). Likewise, they properly describe the gait from an energy standpoint, simulating the change from the kinematic to potential energy during the gait cycle and taking into account the movement depende-

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nce on some external interactions (Xiang et al., 2010). One of the well known models was proposed by Garcia et al. (Garcia et al., 1998) based on the *passive dynamic theory* of McGeer (Garcia et al., 1998): a double articulated pendulum system for which feet are relatively small with respect to the trunk and the heelstrike follows a very restrictive rule. This gait description is still limited because about a 30 % of the gait cycle that corresponds to a double stance phase, is completely eliminated and the CoG displacement in the lateral axis (Y) is not considered at all. Other approaches included the inverted pendulum representation to describe the lateral and frontal CoG motion, but not its vertical displacement, which is assumed constant (Komura et al., 2004).

Other recent approaches are based on optimization techniques and control-based models. The optimization methods include a large number of degrees-of-freedom for producing optimal motions while joint force profiles remain subjected to a large number of constraints(Delp et al., 2007; Fregly, 2008; Xiang et al., 2010). These methods require relatively few data to simulate simple human structures and predict new motions, very useful in computer graphics, robotics and animation applications.The control-based models have been commonly used on robotics and biomechanics for designing the real-time control in biped walking prototipes (Trifonov and Hashimoto, 2008). The main advantage of these methods is that they approximate the actual human control systems, allowing to simulate both normal and pathological gaits. The neuromotor system simulation allows the analysis of some neurological pathologies (Komura et al., 2004), while this is computationally more efficient than the optimization-based models. Nevertheless these methods are computationally expensive and require specific knowlegde of the problem (Xiang et al., 2010) whereby these strategies are highly subjective(Xiang et al., 2010), and also require a large group of experimental data to generate natural motions. This last drawback has highly limited its application in clinical gait analysis because of the specific requirements to obtain a stable and natural motion.

3 MATERIALS AND METHODS

The gait model herein proposed fully describes a 3D CoG trajectory of normal and pathological gaits. The whole model is built upon simple mechanical relationships, approximating the 3D CoG displacement with a double-inverted pendulum for the simple stance phase, and a double spring-mass system for the double stance. Using this physics-based representation, we can animate an human leg structure and simulate normal and pathological kinematic patterns. The kinematic patterns for each case was calculated with a classic method of inverse-kinematic, using the CoG trajectory obtained and a learned heel trajectory taken from some gait laboratory's data as illustrated in figure 1.

3.1 Sagital CoG Description

As a first step, the CoG sagittal trajectory was computed using a physics-based gait representation. The single stance phase (one foot supporting the body) was represented as a double-inverted pendulum. This representation is based on the passive dynamic (Garcia et al., 1998). This model is formulated as a pair of coupled nonlinear equations: $\beta(1-\cos\phi)(3\ddot{\theta}-\ddot{\phi})-\beta\sin\phi(\dot{\phi}^2-2\theta\dot{\phi})+(\frac{g\sin\theta}{l})(\beta(\sin(\theta-\phi)-1))=0$ and $\ddot{\theta}(\beta(1-\cos\phi))-\beta\ddot{\phi}+\beta\dot{\theta}^2\sin\phi+(\frac{\beta g}{l})\sin(\theta-\phi)=0$, where $\beta=m/M$, m is the mass of each foot and M is the body mass, θ is the angle of the supporting leg at a particular time t and ϕ is the angle between both legs. When the leg stance has been accomplished, the heelstrike is represented by the non linear rule$\phi(t)-2\theta(t)=0$. This phase is characterized by the hip and knee moments generated within this interval, important biomarkers in many abnormal movements.

On the other hand, the double stance phase, which starts just after the heel strike, was represented as a double spring-mass system. This physical formulation introduces attenuation as it is usually observed in an actual CoG trajectory because of the knee rotation, but it also involves an intrinsic representation of the muscles acting during this phase. This representation is given by the following equations (Blickhan, 1989): $m\ddot{x}=Px-Q(d-x)$ and $m\ddot{y}=Py+Qy-mg$, where $P=k(\frac{l_0}{\sqrt{x^2+y^2}}-1)$, $Q=k(\frac{l_0}{\sqrt{(d-x)^2+y^2}}-1)$, m is the body mass, x and y are the sagittal and frontal displacement respectively, d in the step length, k is the spring constant, l_0 is the spring lengh at rest and g is the gravity constant (9.81). This physic-based representation describes completely the CoG trajectory and allows to have the flexibility needed to generate different kind of gaits, i.e., pathological gaits.

3.2 Coronal CoG Trajectory

A main contribution of this work is a 3D gait representation that allows to accurately mimic pathological motions like the pelvic balancing (Garcia et al., 1998). The CoG trajectory in the coronal view was simulated using the inverted-pendulum approach. First, we

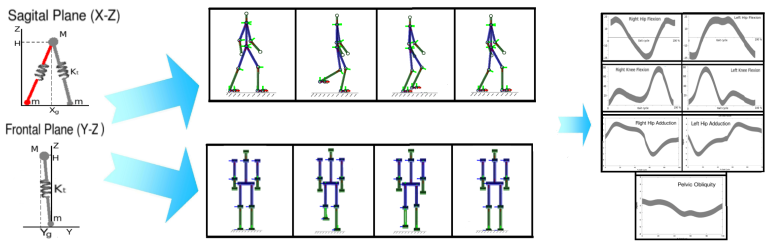

Figure 1: Overview of our proposal. Firstly, it is computed independently the CoG trajectory in both sagittal and coronal views. Then we built up an articulated structure and simulate the human gait using the CoG and a learned heel trajectory using a classical inverse kinematic approach.

calculated independently the CoG motion in both the $x-z$ and the $y-z$ planes (Komura et al., 2004). The CoG trajectory was modeled by a simple inverted pendulum represented by the following equation: $\ddot{y} = \frac{g}{z_i} y$

Where z_i is the CoG heigh at time i (same time for the sagittal view) and g is the gravity constant ($g = 9.81$) (Komura et al., 2004). Given the initial conditions, the CoG trajectory can be described by the following equation: $y = y_0 \cosh \frac{t}{T} + \dot{y}_0 T \sinh \frac{t}{T}$

Where y_0 and $\dot{y}_0$ are the initial conditions and $T = \sqrt{\frac{z_i}{g}}$.

Finally, a complete 3D CoG trajectory was obtained calculating independently both the sagittal and frontal CoG trajectories.

3.3 3D Human Model Representation

This model not only describes the gait in terms of energy, but it also introduces a flexion-extension/adduction-abduction limb description as well as a pelvic obliquity that modify the model dynamics. The kinematic simulation is herein carried out using a classical inverse-kinematic method whose resultant trajectory animates a human-like leg structure, composed of seven articulated rigid segments as illustrated in Figure 1.

3.4 Pathological Gait Simulation

The main advantage of our proposed 3D human representation is that it allows to simulate many kind of movements patterns in both sagittal and coronal views by only tuning the parameters k (the elasticity constant) and d (the step length). With little change in these parameters it is possible to simulate the CoG changes observed in some pathological gaits and to obtain the knee rotation and the CoG attenuation that characterizes some pathological movements. Setting the $k \sim 400$ and $d \sim 0.7$, a normal gait is simulated, but if the k value is increased and/or the d constant is decreased, a pathological gait, for instance the *crouch gait*[1] that characterizes the motion of several cerebral palsy patients (Gage, 2004) is simulated.

4 RESULTS

The evaluation was initially carried out by comparing the CoG trajectory generated by our model with the actual one observed from normal gait trajectories as shown in the figure 2.

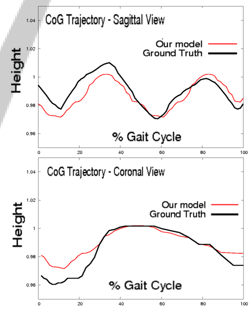

Figure 2: Calculated CoG trajectory in sagittal (top) and coronal view (bottom).

For both sagittal and coronal views, we calculated the correlation coefficient to establish the degree of similarity between both actual and simulated CoG trajectories. The results shows that the correlation coefficient in the sagittal view is 0.85 ± 0.056 and for the coronal view is 0.97 ± 0.013.

4.1 Simulating Normal Gait Patterns

As a second evaluation, we compared the estimated obtained gait kinematic patterns with ground truth trajectories that were obtained from normal patients, as reported in the literature (Gage, 2004), composed of sagittal and coronal patterns of a gait cycle.

[1] This kind of gait is characterized by an exaggerated knee flexion.

As in the previous subsection we calculated the correlation coefficient to establish the degree of similarity between both trajectories, the patterns obtained by our method and the average of each actual normal pattern(table 1).

Table 1: This table shows the correlation factor calculated between both actual and simulated kinematic patterns.

Sagittal View	R. Hip Flex.	0.974 ± 0.016
	R. Knee Flex.	0.71 ± 0.021
	L. Hip Flex.	0.968 ± 0.016
	L. Knee Flex.	0.71 ± 0.021
Coronal View	R. Hip Add.	0.918 ± 0.013
	L. Hip Add.	0.891 ± 0.013
	Pelvic Obliq.	0.876 ± 0.02

4.2 Evaluation for an Actual Pathology

As previously mentioned, one of the main advantages of our model is the possibility of representing pathological gaits by only tuning some parameters of the spring-mass model: The elasticity constant k and the step length d. A crouch gait pattern was simulated by simply increasing the k constant and decreasing the d constant for both frontal and coronal views, as is comment in the section 3 and as shown in figures 3 and 4.

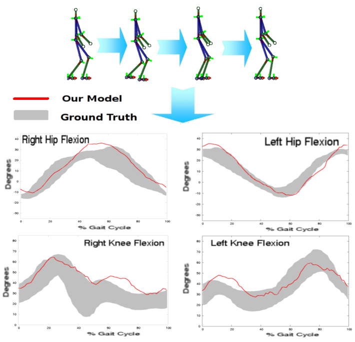

Figure 3: Simulation (top) and generated pathological patterns (bottom) in the sagittal view.

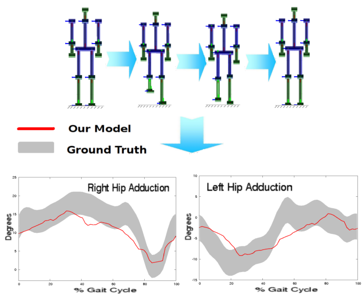

Figure 4: Simulation (top) and generated pathological patterns (bottom) in the coronal view.

The correlation coefficient was calculated to compare the similarity between the patterns obtained and the average of the actual data. The results are shown in the table 2.

Table 2: This table shows the correlation factor calculated between both actual and simulated kinematic patterns.

Sagittal View	R. Hip Flex.	0.9514 ± 0.012
	R. Knee Flex.	0.8638 ± 0.1101
	L. Hip Flex.	0.9529 ± 0.00098
	L. Knee Flex.	0.8810 ± 0.0425
Coronal View	R. Hip Add.	0.9188 ± 0.023
	L. Hip Add.	0.891 ± 0.023

5 CONCLUSIONS

This work has introduced a mechanical gait model which is able to mimic pathological patterns, specifically a gait crouch which is characteristic of the cerebral palsy. This kind of models is a potential useful tool for the physician understands the nature of a particular pattern during the gait. This kind of adapted designs in addition can be a remarkable aide to simulate the evolution of a specific treatment so that treatment planning is possible.

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REFERENCES

Blickhan, R. (1989). The spring-mass model for running and hopping. *Journal of Biomechanics*, 22:1217 – 1227.

Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T., Guendelman, E., and Thelen, D. G. (2007). Opensim open source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng*, 54:1940 – 1951.

Fregly, B. J. (2008). Design of optimal treatments for neuromusculoskeletal disorders using patient-specific multibody dynamic models. *Int J Comput Vision and Biomech*, r:1–31.

Gage, J. R. (2004). *The Treatment of Gait Problems in Cerebral Palsy*. Mac Keith Press.

Garcia, M., Chatterjee, A., Ruina, A., and Coleman, M. (1998). The simplest walking model: Stability, complexity, and scaling. *J Biomech Eng*, d:1–15.

Komura, T., Nagano, A., Kudoh, S., and Shinagawa, Y. (2004). Simulating pathological gait using the enhanced inverted pendulum model. *J Biomech Eng*, r:1–18.

Kuo, A. D. and Donelan, J. M. (2010). Dynamic principles of gait and their clinical implications. *Physical Therapy*, 90(2):157–176.

Trifonov, K. and Hashimoto, S. (2008). Active knee-release mechanism for passive-dynamic walking machines and walking cycle re search. In *IEEE/RSJ Int Conf on Intelligent Robots and Systems*.

Xiang, Y., Arora, J. S., and Abdel-Malek, K. (2010). Physics-based modeling and simulation of human walking: a review of optimization-based and other approaches. *Struct Multidisc Optim*, 42:1–23.