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An Investigation on Ground Reaction Force During Biped Normal Walking

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Abstract
In this paper after reviewing the history of biomechanical researches on biped movement, in order to achieve a deep insight on the structure and bio-mechanics of human body, capability of proposed simple models in predicting ground reaction force (GRF) pattern has been investigated and finally an optimized inverted double pendulum with compliant joints is suggested. The results for GRF pattern during single stance phase for this model were incredibly satisfactory. Beside the great potentials of inverted double pendulum with compliant joints model in explaining the double peak appearance of vertical GRF, it also follows well the kinematical behavior of human leg during single stance phase. These results can be applied vastly in optimizing biped robots and also can be used in other fields like biomechanics, kinesiology and rehabilitation technology.

Keywords: biped, biomechanics, simple models, ground reaction force, kinematical behavior.

Introduction

Special form of motion in order to move from one place to another is called locomotion, studying on human locomotion, biomechanics, control, physiology, and other effective parameters on it’s occurrence and it’s quality have been started since many years ago when Rene Descartes in his trait de l’home et de la formation de foetus, 1675 as the first attempt to contain all animal physiology in mechanical theory, considered the human body as material machine directed by a rational soul [1], and Giovanni Alfonso Borelli, for the very first time related animals to machines and utilized mathematics to prove his theories in his publications, De Motu Animalium I, 1680 and De Motu Animalium II, 1681, the very first comprehensive treaties on bio-mechanics, although at that time it was called iatrophysics, meaning physics applied to medicine [2]. These efforts have been continued up to now and have led to basic and applied consequences. Recently engineers and physiologists have started fundamental researches on bio-mechanics and physiology of animal and human locomotion, meanwhile researches on human walking and running with the aim of understanding and providing a deep insight on the structure and bio-mechanics of human body and it’s physiological role in energy expenditure have been started and progressed. Implication of the obtained results in fields like robotics and rehabilitation technology and specifically in design, control and optimization of biped robots and orthotic and prosthetic limbs have been enormously effective [3]. Despite of the vast understanding of human locomotion and great progress in the field of measurement and processing, the limited movement of individual walking machines and The fact that the stability, agility, and versatility of any existing bipedal machine does not even come close to that of the human biped Shows that understanding from human locomotion has still essential gaps, in which it can be claimed that non of walking machines or biped robots is not optimized individually, so combining all experiments and results of simulations and theoretical studies is necessary to close some of these gaps.

In this way in order to investigate about the capability of suggested models in mimicking human locomotion behavior, some kinetic and kinematical patterns of human locomotion, such as ground reaction force (GRF), vertical oscillation of body center of mass, kinetic and potential energy patterns can be used. Among all of these patterns, competency of biped models’ GRF with human GRF during normal walking is the most controversial, as most biped models are not capable to predict the double peak appearance of vertical GRF during human normal walking.

In this paper after reviewing the physiological and dynamic characteristics of human vertical GRF during normal walking and discussion about conventional walking templates and models and their capability in predicting the double peak appearance of vertical GRF, simple walking templates capable of defining appearance of vertical GRF during normal walking will be suggested and discussed in details. Finally the relationships between vertical GRF and kinematics of locomotion system’s segments will be discussed.

Vertical Ground Reaction Force

The GRF is a three-component vector representing the forces in the vertical, anterior-posterior and medial-lateral planes. Each component measures a different characteristic of movement. The vertical component is primarily generated by the vertical acceleration of the body and is of highest magnitude [4]. In the remainder of this paper the term ground reaction force (GRF) refers to the vertical component only, unless stated otherwise.
In the following sections The GRF for normal walking will be discussed. The GRF is normalized by body weight (normalized GRF = GRF/Body weight).

As it is shown on "Figure 1", vertical GRF diagram for human during normal walking, has two peaks one at the beginning of single stance phase and the other at the end of this phase. The double peak appearance is a unique form for normal walking, and other motions have different GRF diagram, for example running has a mono-peak diagram. So GRF appearance can be used in movement analysis and in addition to determining the type of movement it can also convey more information about the quality of locomotion behavior.

According to physiologic researches and models defined for human walking, contrary to what had been supposed, heel up in mid-swing and knee flexion in stance phase don't cause the double peak appearance of human GRF during normal walking [5] and even contra lateral leg swing motion doesn't have any role in this unique shape [6]. But this is the hip and knee extensors in early stance [7, 8] and the plantar flexors and rectus femoris force in late stance [7] which play main roles in formation of the first and second peaks in the vertical ground reaction force.

Biped Models

Up to now several simple and complicated models and templates have been suggested for studying biped locomotion, but the great virtues of a simple model is that they possess only a few variables. The fewer the variables, the easier it is to understand the relationships between cause and effect or in other words the relationships between mechanical and biomechanical parameters of the human body and the quality of the gait during locomotion, so this is why we discuss mostly about simple models in our project, but due to limitations to this approach, models of exceeding complexity have been built to learn more about some details and complexity such as investigation on how muscles coordinate motion of the body segments in normal locomotion [9]. In the following paragraphs the advantages and disadvantages of some simple models previously suggested for normal walking will be discussed and then an optimized model capable of predicting GRF appearance will be discussed in details.

In order to verify, whether the suggested models are convenient ones for defining biped behaviors or not, we used Ground Reaction force pattern. By producing the related diagrams and schemes and comparing with those exploited from experimental projects on human body we can decide about the verification of suggested models.

Inverted Single Pendulum

Cavagna (1976) introduced the simplest of all models [10], the inverted pendulum, to understand the changes in kinetic and potential energy that occur when humans walk at their natural speeds. the inverted pendulum predicts that fluctuations in kinetic and potential energy in normal walking correctly, but it is not an appropriate model for studying vertical movements of the centre of mass, and therefore ground reaction force patterns, in walking [9].

Inverted Double Pendulum

Due to the weakness of the simple inverted pendulum in predicting the double peak appearance of vertical GRF plot, Inverted double pendulum model was introduced by Pandy [9] to model the single-leg stance phase of walking. As the contralateral leg is not represented explicitly in this model, double-leg stance is excluded from consideration. This model has more similarity to the biomechanics of human leg.

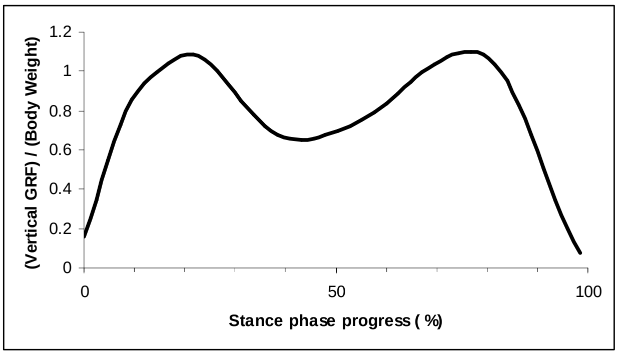

Figure 1: Ground reaction force plot during human normal walking.

Although in some reports and papers [9] has been claimed that the double inverted pendulum with simple stiff links and joints can predict two peaks of human GRF plot during single stance phase, but according to our models and simulations it can not predict the double peak trend in human GRF plot, but the results from these researches show the potentials of this model but indeed it needs to be optimized in order to be able to define most kinetic and kinematical characteristics of human normal walking.

Inverted Double Pendulum with Compliant Joints

In order to optimize the inverted double pendulum model and to increase it's capability in defining locomotion behaviors (especially walking) characteristics and also to investigate about the effects of biomechanical and biological elements such as leg segmentation and joints compliancy in the quality of motion , we introduced double inverted pendulum with compliant knee and ankle joints model, "Figure 2". It was the same as the inverted double pendulum model but with flexible knee and ankle joints, which their stiffnesses were optimized through genetic algorithm method. The results for ground reaction force pattern during single stance phase for this model was incredibly satisfactory. Beside the great potentials of inverted double pendulum with flexible joints model in explaining the double-peak appearance of vertical ground reaction force, it also follows the kinematical behavior of human leg during single stance phase.

Inverted double pendulum is a two degree of freedom model ("Figure 2"). According to the dynamics of this model and by forming the Lagrange equation for it, the dynamic equations of the inverted double pendulum with compliant knee and ankle joints can be obtained. In this model m3 is the total equivalent mass of head and trunk and also the swing leg mass which can freely rotate relative to hip, m1 and m2 are the equivalent mass of shank and thigh. T1,T2 and T3 are respectively the equivalent applied moments on ankle, knee and hip joint which are the resultant of the several muscles moments.

L1 and L2 are the length of the shank and thigh . θ_1 and θ_2 shows respectively the angular displacement of ankle and knee. K1 and K2 are the ankle and knee joints stiffness. In order to have the ground reaction forces of this model first of all the obtained equations of motion should be solved numerically (Second order Taylor series) for θ_1, θ_2 and their first and second derivatives, then the vertical GRF plot can be produced for this model. For entering the values of m1, m2,m3, L1 and L2 we used the anthropometric data, "Table 1", [11] and also for T1 and T2 the kinetic data obtained from experimental researches [11] were used . Optimized values of K1 and K2 should be obtained through the genetic algorithm program which was written for this project.

In order for reaching the optimized values for K1 and K2 by genetic algorithm we used the experimental data of human vertical GRF during normal walking [11] as fitness value in the optimization program.

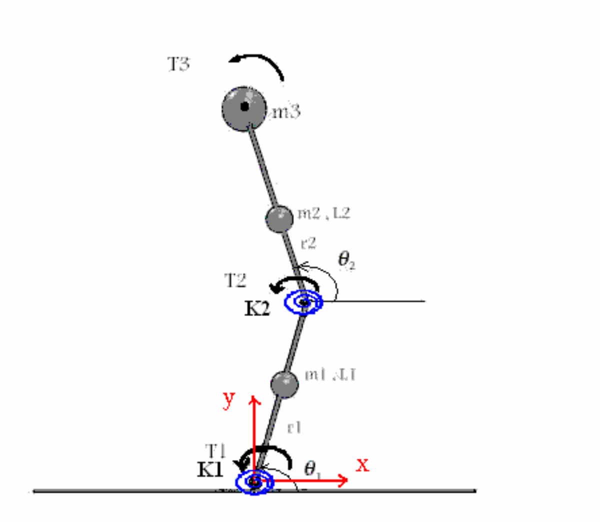

Figure 2: Inverted double pendulum with compliant knee and ankle joints.

Table 1. Inverted double pendulum parameters

m_1	m_2	m_3	I_1	I_2
2.84kg	7.12kg	46.74kg	0	0
I_3	l_1	l_2	r_1	r_2
0.5 kgm^{-2}	0.342m	0.327m	0.194m	0.188m

Genetic Algorithm Program

In our program the optimized parameters are ankle and knee joints stiffness values, K1 and K2. The fitness function is based on the experimental data of human vertical GRF during normal walking [11]. In this optimization the algorithm tries to minimize the amount of fitness value. The selection algorithm is the roulette wheel, which selects the individuals according to the inverse amount of fitness value.

The set values of the genetic algorithm parameters for optimizing the inverted double pendulum model with flexible joints are shown in "Table 2". "Table 3" contains the initial values for angular displacements and velocities of shank and thigh link, which are extracted from experimental data [11], this table also shows the optimum values of K1 and K2.

Table 2: Initial values and optimum values

Genetic algorithm parameters	set values
Cross Over Probability **(PC)**	0.9
Selection Probability **(PS)**	0.45
Mutation Probability **(PM)**	0.7
Population size	1500
Genome Number	100
String Length	14

Table3: Set values of the genetic algorithm parameters

Parameters	**Initial values**
$(\theta_1)\|_{i=1}$ Shank angular position	rad 1.57
$(\theta_2)\|_{i=1}$ Thigh angular position	1.847 rad
$(\dot{\theta}_1)\|_{i=1}$ Shank angular velocity	-1.88 rad/s
$(\dot{\theta}_2)\|_{i=1}$ Thigh angular velocity	-1.45 rad/s
Joints stiffness	**Optimized values**
k_1 Ankle joint	28 Nm/rad
k_2 Knee joint	20 Nm/rad

Results and Discussion

As it is depicted in “Figure 2", the GRF plot for inverted double pendulum model with flexible joints is so similar to the human one during single stance phase of normal walking which has a double peak appearance. The capability of this model in predicting the appearance of human GRF during walking finds multiple importance when it is observed that the kinematical behavior of he model’s leg segments (shank and thigh) is so close to the kinematics of human leg during single stance phase, "Figure 4" and "Figure 5", and also knee angular displacement is so similar to human knee displacement, "Figure 6", and the differences at the end of this phase are due to the simplicity we have considered in the model’s knee in compare to human knee.

Conclusions

By investigating about the advantages of inverted double pendulum model with compliant joints in defining human walking characteristics in compare to previous suggested simple models we came to this conclusion that this capability is due to considering some biomechanical and biological aspects of human locomotion system, such as considering shank, thigh , knee and ankle in this model and also knee and ankle compliancy. It can be claimed that by considering more biomechanical and biological aspects of human locomotion system in our biped models, they can define and predict the human locomotion behavior characteristics better.

As it was explained, this model vertical GRF is so

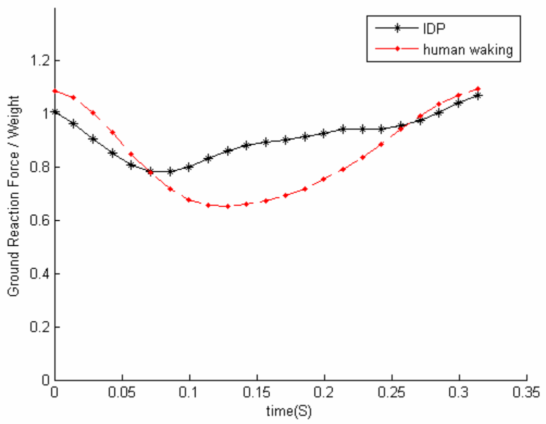

Figure 3: Vertical GRF plot for inverted double pendulum model with compliant knee and ankle joints, and human during single stance phase of normal walking.

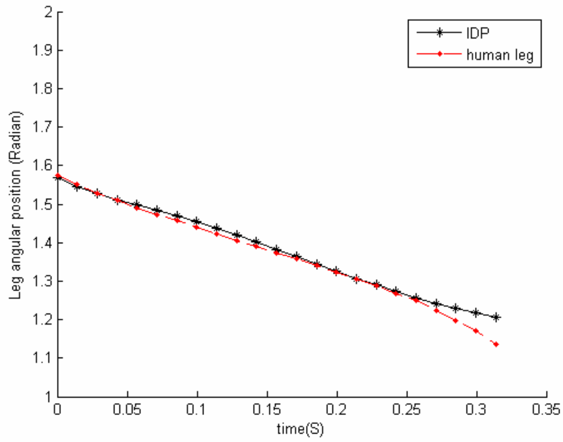

Figure 4. Shank angular position for inverted double pendulum model with compliant knee and ankle joints, and human during single stance phase of normal walking.

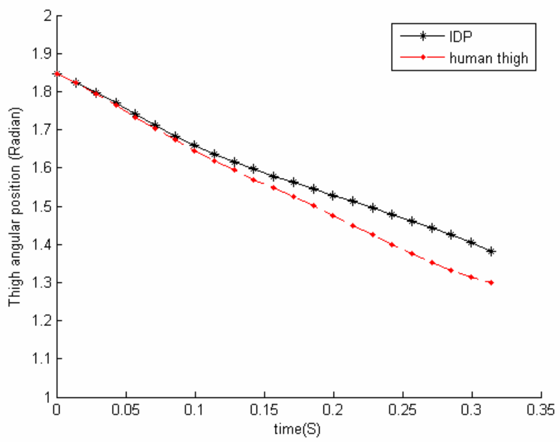

Figure 5. Thigh angular position for inverted double pendulum model with compliant knee and ankle joints, and human during single stance phase of normal walking.

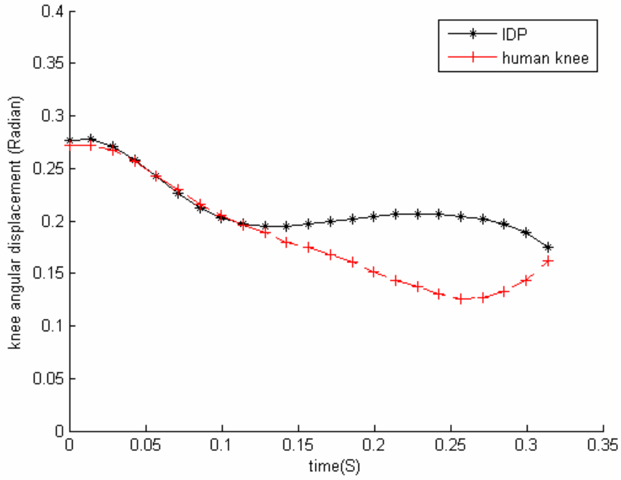

Figure 6: Knee angular displacement for inverted double pendulum model with compliant knee and ankle joints, and human during single stance phase of normal walking.

similar to human GRF plot during normal walking, and also the kinematical behavior of the leg segments is so close to human leg kinematics during single phase of normal weakling. By observing these advantages and also observing this trend that as much as the model's vertical GRF plots are closer to human GRF, the kinematical behavior of the model become closer to kinematics of human leg, so we can use GRF as an optimizing parameter for optimization of kinematics of biped systems. Of course in order to prove this assumption we need to investigate it in some more complex biped models.

References

[1] Descartes, R., 1675. *Trait de l'home et de la formation de la foetus.* Elsevier, Amsterdam.

[2] Maquet, P., 1992. "Iatrophysics to Biomechanics". *JBone Joint Surg [Br]*. 74-B, pp. 335-9.

[3] Ferris, D. P., Czerniecki, J. M., and Hannaford, B., ,2005. "An Ankle-Foot Orthosis Powered by Artificial Pneumatic Muscles". *Journal of Applied Biomechanics*, 21, pp. 189-197.

[4] Headon, R., Curwen, R.,"Recognizing Movements from the Ground Reaction Force", In Proceedings of the 2001 workshop on Perceptive user interfaces.

[5] Mochon, S. and McMahon, S., 1980. "Ballistic Walking". *J. Biomech*. 13, pp. 49–57.

[6] Pandy,M.G.' Bereme, N., 1989. "Quantitative Assessment of Gait Determinants During Single Stance via a Three-Dimensional Model-Part 1. Normal Gait*". J. Biomechanics*, Vol 22, No 6/l, pp. 717-724.

[7] Neptunea, R.R., Sasakia, K., Kautz, S.A., 2008. "The Effect of Walking Speed on Muscle Function and Mechanical Energetics". *Gait and Posture*, Vol 28(1), pp. 135–143.

[8] Pandy, M.G., 2003. "Simple and Complex Models for Studying Muscle Function in Walking". *Phil. Trans. R. Soc. Lond. B*, 358, pp. 1501–1509.

[9] Pandy, M. G., 2001. "Computer Modeling and Simulation of Human movement". *A. Rev. Biomed. Engng* ***3***, pp. 245–273.

[10] Cavagna, G. A., Thys, H. and Zamboni, A., 1976. "The Sources of External Work in Level Walking and Running". *J. Physiol.* , 262, pp. 639-657.

[11] Winter, D.A., 2009. *Biomechanics and Motor Control of Human Movement*. Fourth Edition, John Wiley & Sons, Inc.