The Study of the Effect of Variation of Human Parameters on the Walking Speed Based on Simulations

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Abstract. This paper aims to the purpose of this paper is to establish a mechanical model of biped walking based on passive walking theory, and conduct simulation research using national standard human body parameters. The influence of changes in human body parameters on walking speed was analyzed. It draws the conclusion that the "length of the shank and foot height" and the (length of the shank and foot height)/the length of leg)" have positive correlation with the walking speed. And this appearance is in compliance with other researchers' results by experiments. This method can be used for walking races athlete selection.

Keywords: walking races · passive walk · human parameters · biped walking model

1 Introduction

Race walking is a sport that pursues the ultimate speed of biped walking. Advanced technology and athlete selection are the foundation for achieving good results.

Previous studies have conducted relevant studies on the sports characteristics, body shape, and performance of race walking athletes. Lang Xuemei conducted biomechanical research and analysis on the sports videos of elite female race walking athletes in China, and proposed suggestions for improvement [1]. Wang Guowei analyzed and diagnosed the technical characteristics of players in the National Walking Race Championship [2]. Liu Yanzhu analyzed the dynamic process of human biped walking, discussing the mechanics of race walking and running [3]. Li Houlin proposed the conclusion that "the principle of race walking technology is to synchronize the pendulum term of a single support periodic motion of 'near fixed positive pendulum motion' and 'far fixed inverted pendulum motion' through the analysis of motion images" [4]. Chen Tuyu conducted a kinematic analysis of the walking techniques of Chinese athlete Wang Kaihua and compared his differences with international elite athletes [5]. Hua Li determined five indicators, including leg length and foot height, weight/height * 1000, ankle circumference/lower limb length, foot height, (leg length and foot height)/lower limb length, as the basis for the evaluation model of race walking athletes by measuring and analyzing the physical parameters of 50 female race walking athletes, and the comprehensive scoring criteria have a high correlation with the athletes' performance grades [6].

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In the above research, the main focus is on the analysis and processing of measured data and kinematic image data obtained from experiments, revealing the movement rules of race walking based on experimental data, or providing a reference for talent selection through correlation analysis of race walking athletes' morphological parameters and performance. However, these studies are mostly conducted on certain athletes at the scene of competition or in the laboratory, and the experimental results are influenced by motion capture conditions and individual differences among the subjects.

From a mechanical perspective, biped walking is a dynamic process with strong nonlinearity. The process of single foot support presents an unstable inverted pendulum configuration, but the alternating support of two feet makes the unstable inverted pendulum motion form a stable walk. In the late 1980s, McGeer proposed the theory of "Passive Dynamic Walking", believing that human walking is largely carried out using gravity, providing energy input only at the moment of landing [7]. The phenomenon of passive bipedal walking is very similar to that of human walking. Figure 1 shows a comparison between the continuous animation of passive walking and the simplified stick graph of human walking video [8].

The bioelectricity test experiment on human walking found that during normal walking, the electrical signals of the muscles of the support leg gradually increase from the start of support during the entire support period, reaching their peak and rapidly decaying when the foot starts to pedal, while the electrical signals of the muscles of the swing leg are very weak. This provides an experimental basis for the argument that bipedal walking is partially passive [9, 10]. Through research on passive walking, it is found that walking gait is greatly influenced by model parameters, and for a fixed set of model parameters, only a stable set of gait can be found [11].

This article uses the method of dynamic simulation analysis, based on a planar passive walking model, and using national standard adult human body inertia parameter data, to conduct dynamic simulation of the biped walking process, study the impact of foot radius, leg length, and mass characteristic parameter changes on walking gait and speed, and compare and analyze with the laws in the literature, in an attempt to provide a reference for subsequent dynamic research on race walking.

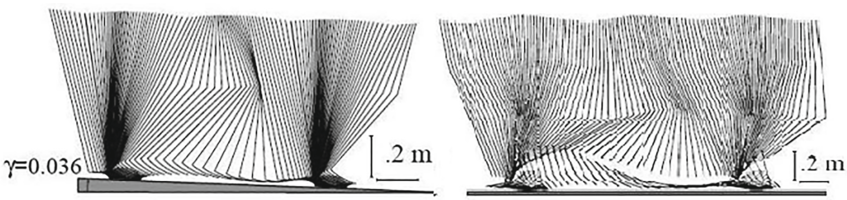

Fig. 1. The simulation and the human walking snapshots in Garcia's thesis [8]

2 Methods

2.1 Object

The biped walking problem is simplified into a dynamic model. Based on the results of other researchers [11], the model studied in this paper adopts the following simplified assumptions:

a. The model walks on a downhill slope, and the energy source is gravitational potential energy.
b. The movement of the model is in the sagittal plane of anatomical significance.
c. The legs of a biped walking model are considered rigid bodies and simplified to a rod-shaped leg model. Regardless of the thickness of the legs, the center of mass of the legs is located on the rod, with non-uniform distribution of mass.
d. The hip and knee joints are simplified to frictionless rotation.
e. The foot is in a circular arc and is firmly attached to the leg at the ankle joint, ignoring the mass of the foot.
f. During the non-foot collision time, the pure rolling between the support foot and the ground is approximately.
g. The collision between the swinging foot and the ground is a completely inelastic collision, regardless of the collision time.

The model diagram is shown in Fig. 2. The thigh length is l_t, mass is m_t, distance from the center of mass to the hip joint is c_t, and the rotational inertia relative to its center of mass is J_t; The corresponding parameters for the lower leg are l_s, m_s, c_s and J_s; The foot radius is r; The length (l_t), mass (m_t), center of mass (c_l), and moment of inertia of the entire leg (J_l) are calculated based on the parameters of the big and small legs. The inclination angle of the slope is γ and the acceleration of gravity is g. Let the corresponding generalized coordinates of leg 1 and leg 2 be θ_1 and θ_2, and the generalized coordinates of the lower leg of the swinging leg be θ 2s.

The second type of Lagrange equation is used to derive the dynamic equation of the system. The general form of the second type of Lagrange equation is:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q} = Q_i \quad (i = 1, 2 \cdots f)$$

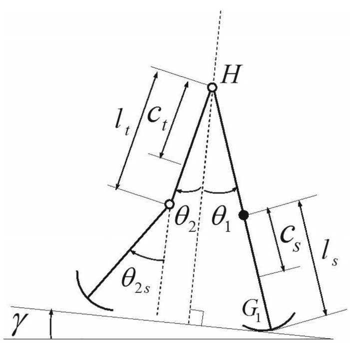

Fig. 2. The sketch of the kneed model [11]

$L = T - V$ is the Lagrange function.

The differential equation of motion of the system is

$$\begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_{2s} \end{bmatrix} = \begin{bmatrix} f_1(\theta, \dot{\theta}) \\ f_2(\theta, \dot{\theta}) \\ f_3(\theta, \dot{\theta}) \end{bmatrix}$$

$$M_{11} = [(4l_l - 2c_l) - 4r]m_l r \cos\theta_1 + [4r^2 + (-4l_l + 2c_l)r + c_l^2 - 2l_l c_l + 2l_l^2]m_l + J_l$$

$$M_{22} = m_t c_t^2 + m_s l_t^2 + J_t$$

$$M_{33} = m_s c_s^2 + J_s$$

$$M_{12} = M_{21} = [(m_t c_t + m_s l_t)r - m_t c_t l_l - m_s l_t l_l]\cos(\theta_2 - \theta_1) - (m_t c_t + m_s l_t)r\cos\theta_2$$

$$M_{13} = M_{31} = (-l_l + r)m_s c_s \cos(\theta_{2s} - \theta_1) - m_s c_s r \cos\theta_{2s}$$

$$M_{23} = M_{32} = m_s c_s l_t \cos(\theta_2 - \theta_{2s})$$

$$\begin{aligned} f_1 = {} & [(-r^2 + r l_l)m_s + (-m_t - m_l)r^2 + ((l_l - c_l)m_l + m_t l_l)r]\dot{\theta}_1^2 \sin\theta_1 \\ & +[(-m_s l_t - m_t c_t)r\sin\theta_2 + ((l_t l_l - l_t r)m_s + m_t c_t l_l - m_t c_t r)\sin(\theta_1 - \theta_2)]\dot{\theta}_2^2 \\ & +[(-c_s r + c_s l_l)m_s \sin(\theta_1 - \theta_{2s}) - m_s c_s r \sin\theta_{2s}]\dot{\theta}_{2s}^2 \\ & +(2l_l - c_l - 2r)m_l g \sin(\theta_1 - \gamma) - 2m_l g r \sin\gamma \end{aligned}$$

$$\begin{aligned} f_2 = {} & [m_s l_t l_l + m_t c_t l_l - (m_l l_t + m_t c_t)r]\dot{\theta}_1^2 \sin(\theta_2 - \theta_1) \\ & -m_s c_s l_t \dot{\theta}_{2s}^2 \sin(\theta_2 - q2s) \\ & -[m_t c_t + m_s l_t]g\sin(\theta_2 - \gamma) \end{aligned}$$

$$f_3 = (l_l - r)m_s c_s \dot{\theta}_1^2 \sin(\theta_{2s} - \theta_1) + m_s c_s l_t \dot{\theta}_2^2 \sin(\theta_2 - \theta_{2s}) - m_s c_s g \sin(\theta_{2s} - \gamma)$$

2.2 Methods

Dynamic simulation

Given the anthropometric parameters in the above model, the dynamic equation is solved using Matlab programming to obtain a curve of the gait that the model can stably walk over time, and then the walking speed is calculated. In order to make the model parameters representative, the adult female body segment parameters in the national standard "Adult Human Body Inertia Parameters" [12] are selected, and the data are listed in Table 1.

Based on the above data, the length (l_l), mass (m_l), center of mass (c_l), and rotational inertia of the entire leg (J_l) can be calculated. The gravity acceleration is 9.8kg/s2, the

Table 1. The inertial parameters of adult women in the National Standards [12]

Index	National Standard Data	Remarks
Thigh Mass (m)	7.52 kg	
Thigh Centroid Position (c_t)	244.5 mm	$c_t = 193.67$ mm
Calf Mass (m)	2.36 kg	
Calf Centroid Position (c_t)	197.6 mm	$c_t = 146.05$ mm
Rotational Inertia Of Thigh (J_t)	102537 kg·mm^2	
Rotational Inertia Of Calf (J_t)	20092 kg·mm^2	
Relative Position Of Thigh Centroid (l_t)	44.2 mm	$l_t = 438.17$ mm
Relative Position Of Calf Centroid (l_s)	42.5 mm	$l_s = 343.65$ mm

foot radius is 0.4 times the leg length, and the slope angle is 0.2 rad. Carry out simulation calculations.

Setting of simulation parameters

In Huali's research, five indicators, including leg length plus foot height, (weight/height) * 1000, ankle circumference/lower limb length, foot height, (leg length plus foot height)/lower limb length, were used as indicators for the evaluation model of race walking athletes' body shape, and comprehensive scoring criteria were given respectively, and the athletes' body shape was scored. Among them, the four indicators of leg length plus foot height, (weight/height) * 1000, foot height, and (leg length plus foot height)/lower limb length are all rated high by those with high values, while those with high comprehensive ratings have a large proportion of high athletic performance, that is, the values of the above indicators are positively correlated with athletic performance [6].

In order to facilitate comparison with the experimental data rules of existing studies, this study analyzed the impact of two parameters, namely leg length plus foot height and (leg length plus foot height)/lower limb length, on walking speed in the model.

According to national standard data, the average value of leg length plus foot height for adult women in China is 0.41 m. In the measured data of Huali, the parameter range is between 0.39–0.45 m. To cover the range of experimental samples, the simulation calculation of this study sets the parameter change range to 0.38–0.48 m [6].

In addition, this study also considered the impact of changes in the lower limb length and foot radius on speed, and conducted relevant simulation analysis in order to accumulate reference data for subsequent experiments.

In the national standard data, the average lower limb length of adult women in China is 0.79 m. In this study, the range of simulation parameters is set to 0.71–1.00 m.

According to simulations and experiments by other passive walking researchers, setting the foot radius at about 0.4m can achieve a relatively stable gait, and is close to the gait of a human walking [7, 10]. Therefore, this study sets the variation range of simulation parameters to 0.395–0.435 m.

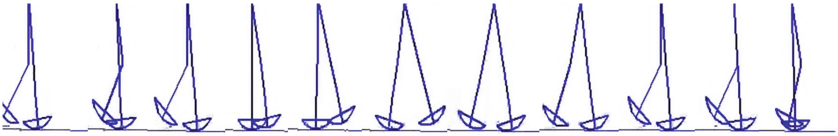

Fig. 3. The snapshots of the walking simulation of the kneed model [12]

3 Results

3.1 Walking Speed Simulation

According to the national standard "Inertia Parameters of Adult Human Body" [12], the data of adult female body segment parameters are listed in Table 1. A screenshot of the walking action is shown in Fig. 3. The simulation calculation shows that the average walking speed in the horizontal direction is about 1.42 m/s, or 5.1 km/h, which is equivalent to the walking speed of ordinary people. This indicates that the model simulation method in this study is effective.

3.2 Impact of Leg Length Plus Foot Height on Walking Speed

Leg length plus foot height is one of the important length factors that affect the performance of race walking athletes. In this study, the variation range of leg length plus foot height is set to be 0.38–0.48 m, and three foot radius (r) values, namely 0.40 m, 0.41 m, and 0.42 m, are set. Multiple sets of simulations are conducted. The resulting stable gait walking speed is shown in Fig. 4.

As can be seen from Fig. 4, with the increase of the leg length plus foot height value, the stable walking speed gradually increases. The correlation analysis shows that the leg length plus foot height parameter has a high positive correlation with walking speed at the 0.01 level ($r = 0.4$ m, $p = 0.970$; $r = 0.41$ m, $p = 0.991$; $r = 0.42$ m, $r = 0.982$), which is the same trend as the experimental research conclusions of Huali [5]. In the measured data of Huali [6], the range of leg length plus foot height is 0.390–0.456 m. In its evaluation indicators, this parameter is used as a length factor in the first level index, with a weight of 42%. It can be seen that the leg length plus foot height parameter is a key factor to be considered in the selection of race walking athletes. The larger this parameter, the more advantageous it is for improving speed. In addition, when the leg length plus foot height value is fixed, the foot radius increases, and the corresponding walking speed also increases.

3.3 (Leg Length and Foot Height)/Effect of Lower Limb Length on Walking Speed

(Leg length and foot height)/lower limb length is one of the main length ratio factors that affect the performance of race walking athletes in body shape indicators. In this study, the variation range of (lower leg length and foot height)/lower limb length is set 0.50–0.56 m, and three foot radius (r) values of 0.40 m, 0.41 m, and 0.42 m are taken for multi group simulation. The resulting stable gait walking speed is shown in Fig. 5.

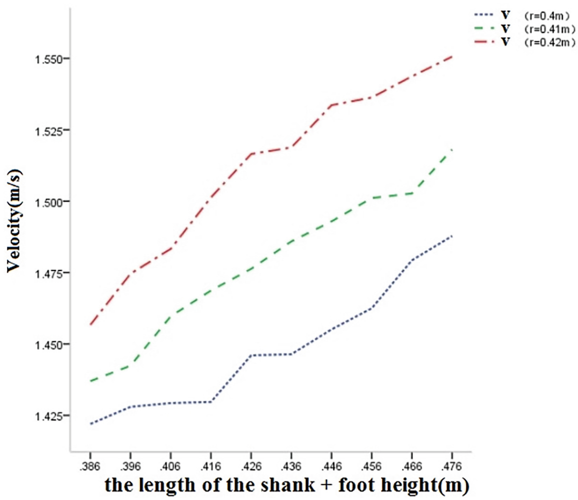

Fig. 4. The relationship of "the length of the shank and foot height" and the walking speed

As can be seen from Fig. 5, with the increase of the (leg length and foot height)/lower limb length value, the stable walking speed shows a wave like upward trend. The correlation analysis showed that at the 0.01 level, there was a high positive correlation between walking speed and (leg length plus foot height)/lower limb length ($r = 0.4$ m, $p = 0.984$; $r = 0.41$ m, $p = 0.989$; $r = 0.42$ m, $p = 0.987$), which was consistent with the trend of Huali's [5] experimental research conclusions. Of course, Huali [5] have studied the five indicators included in the body shape characteristics index system and weight of young female race walking athletes in China. The weight of (leg length and foot height)/lower limb length is 7%, while the weight of leg length plus foot height is 42%. This also indicates to some extent that there are differences in the correlation between the two indicators and speed, which is consistent with our research results. At the same time, similar to the leg length plus foot height parameter, the fixed (leg length and foot height)/lower limb length value also exhibits an increasing trend in walking speed as the foot radius increases.

3.4 Simulation Analysis of Other Parameter Changes

Based on the good agreement between the aforementioned simulation results and the laws obtained from experimental data, and taking into account the characteristics of the indicators and the need for follow-up work, we conducted simulation analysis on the impact of changes in the lower limb length and foot radius on speed.

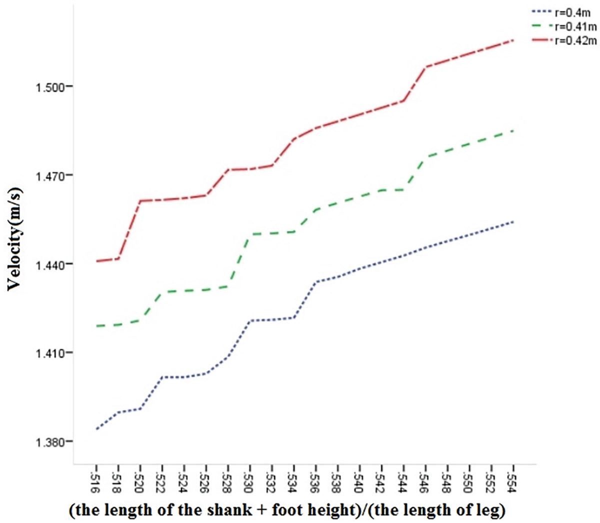

Fig. 5. The relationship of (the length of the shank and foot height)/ (the length of leg) and the walking speed

The lower limb length is set 0.71–1.0 m. Similarly, three foot radius values of 0.40 m, 0.41 m, and 0.42 m are set to simulate the relationship between lower limb length and walking speed under different foot radius.

In order to obtain a relatively stable gait and approximate the gait of a person walking [8, 11], this study sets the variation range of foot radius simulation parameters to 0.395–0.435 m, and sets three different starting ramps.

As can be seen from Fig. 6, there is a positive correlation between the speed of stable gait and lower limb length parameters. The correlation analysis results show that there is a high correlation between lower limb length and walking speed at the 0.01 level (r = 0.4 m, p = 0.996; r = 0.41 m, p = 0.995; r = 0.42 m, p = 0.998) for all three foot radius.

The legs of the simulation model are simplified as circles, and their contact with the ground is simplified as pure rolling. Set the foot radius to be within the range of 0.395–0.435 m and the starting ramp angles to be 0.20, 0.21, and 0.22 radians, respectively. Figure 7 shows the rule of change between the foot radius and the steady walking speed. The results show that as the foot radius value increases, the steady walking speed increases. Correlation analysis showed that there was a high positive correlation between foot radius and stable gait speed at the 0.01 level ($gama = 0.2$, $p = 0.999$; $gama = 0.21$, $p = 0.991$; $gama = 0.22$, $p = 0.988$).

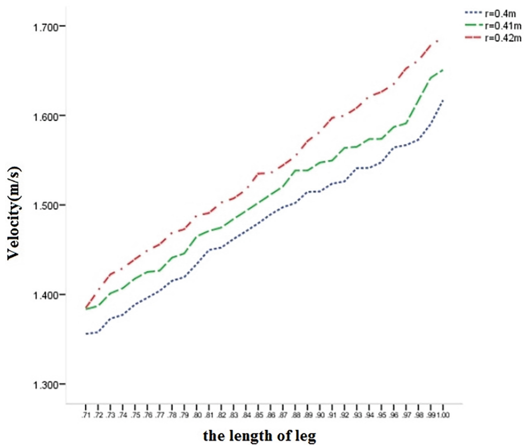

Fig. 6. The relationship of the length of leg and the walking speed

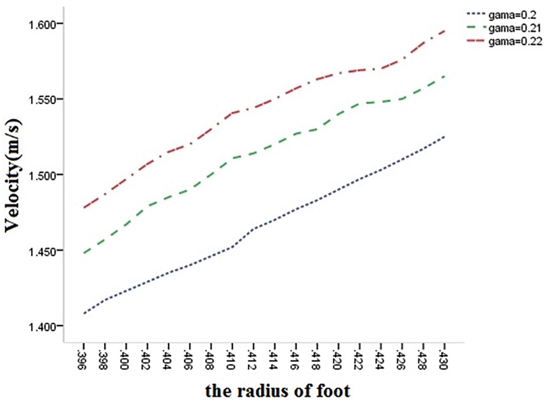

Fig. 7. The relationship of the radius of foot and the walking speed

4 Conclusion

In this paper, a simplified dynamic model of biped passive walking was established, and the dynamic simulation of biped passive walking was conducted using national standard human body data. The influence of human body parameter changes on walking speed was studied. The analysis of simulation results shows that the changes in leg length and foot height parameters are significantly positively correlated with walking speed, and the changes in (leg length and foot height)/leg length parameters are also significantly positively correlated with walking speed in most cases. These two trends are consistent with the correlation between parameters and performance obtained by analyzing the body data of 50 race walking athletes in the literature [12].

The simulation results of the two parameters lower limb length and foot radius, also show that they are positively correlated with walking speed. These two conclusions are more consistent with common sense, but require quantitative experimental data support. At the same time, there is no discussion on the impact of foot radius on race walking performance in existing studies. Further experimental research is needed to determine which type of anthropometric parameter foot radius should correspond to, and whether it can match the rule of foot length variation.

The rules of parameter changes and walking speed provided by this simulation method can provide a certain reference for the formulation of future competition walking material selection standards.

References

1. Lang Xuemei, Ji Zhongqiu, Biomechanical Analysis of the Walking Techniques of Chinese Elite Female Walking Athletes [J]. China Sports Science and Technology, 2003, 39 (4): 31-35
2. Wang Guowei, Zhou Haoxiang. Technical Analysis and Diagnosis of China's Outstanding Female 20km Walking Race Athletes [C]. 22nd National Sports Biomechanics Academic Exchange Conference, 2022.
3. Liu Yanzhu, Mechanical Analysis of Biped Walking and Jumping [J]. Mechanics and Practice, 2008, 30 (3): 47-51.
4. Li Houlin, Research on the Application of "Composite Pendulum" Sports Biomechanical Principles in Technological Innovation of Walking Race [J]. Journal of Xi'an Institute of Physical Education, 2013 (2): 196-203
5. Chen Tuyu, Sun Luxin, Guo Piyong. Kinematic Analysis of Key Techniques of Chinese Men's 20km Excellent Walking Race Athlete Wang Kaihua [C]. 30th National University Track and Field Scientific Research Paper Conference, 2020.
6. Hua Li, Research on the Body Shape Characteristics and Evaluation Model of China's Excellent Young Female Walking Race Athletes [D]. Master's Thesis of Yunnan Normal University, 2008.
7. McGeer T., Passive dynamic walking [J]. International Journal of Robotics Research, 1990, 9(2):62-82.
8. Garcia M., Stability, Chaos, and Scaling Laws, Passive–Dynamic Gait Models [D]. USA: Cornell University, 1998.
9. Basmajian, J. V. and Tuttle, R., EMG of locomotion in gorilla and man [M].Plenum Press, New York, 1973.
10. Winter D. A. The biomechanics and motor control of human gait: normal, elderly, and pathological [J], Biomechanics & Motor Control of Human Movement, 1991, 74 (2) :369-384.
11. Zheng Qi. Research on Limit Cycle Walking of Passive Biped Robot [D]. Harbin Institute of Technology, 2021.
12. GB/T 17245–2004, Human Body Inertia Parameters for Adults, National Standard of the People's Republic of China.