Recreating evolutions of human walking gesture by spring-mass walking model

Luopeng Yin

Jiangnan University, Wuxi, 214026, China

1044210119@stu.jiangnan.edu.cn

Abstract. The evolution of human walking gestures is the evolution to adapt to new environments. Evolutionary adaptations in humans, including longer, straighter legs and increased average BMI, were examined using a spring-mass walking model to analyze their impact on locomotion efficiency. Spring-mass model considers walking problems in mechenics dimension. The simulation seperates variations that affects human walking to four independent parameters: mass, touch-down degree, leg length and leg stiffness. Simulation results demonstrated that model has lighter mass, which walks in smaller touch-down degrees gaits by lengthened, robust legs improved walking efficiency. By comparing CM displacement, research also addressed discrepancies between flat and normal gaits. Flat walking compensates its forward moving efficiency and distance per step to gain smaller vertical CM amplitude, accompanied by larger vertical CM amplitude and slower walking speed. Stronger legs and a curved, large-step gait reduced knee and waist pressure in individuals with higher BMI. The study highlights the adaptive significance of human physiological evolution in relation to locomotion efficiency. The study will provide insights into bipedal explanation for evolution tendency and existing problems.

Keywords: spring-mass walking model, walking efficiency, bipedal simulation, CM, human evolution.

1. Introduction

Human ancestors used to walk in curved leg gestures in a compliant pattern with low speed to survive in arboreal environments[1]. Then they managed to hunt in the ground and walk long distances searching for food and a better living place[2]. Thus, ancestors lengthened their legs and kept their legs straight in walking, then evolved stronger legs to migrate. Human evolved leg structures that adapt to flat and flexed ground. One existing problem in human walking is why flat walking has less moving efficiency than normal walking, which is irrelevant to walking speed.

Another tendency for evolution is higher BMI, which is caused by better nutrition systems and unhealthy living habits in modern cities. Compared to healthy people, they walk slower and have less step distance. Also, they pay more attention to keeping their body balanced[3].

An interesting subject in engineering science is the field of bipedal robots, which is inspired by human locomotion[4]. Among numerous robotic models, Spring-Mass walking model represents stiff and compliant walking gesture in bipedal field[5]. Altough human legs are quite complex in structure and simulation in computer,it also can simplified as many simple models, e.g., bouncing gaits[6][7], compliant quadrupted walker[8].

Spring-like leg behaviour could be produced by technical springs in the leg, also could be produced by simulating elasticity with actuators. Altough simple linear spring may not exist in nature, spring-like structure could be seen.

This study first builds a simulation environment in MATLAB, plot out CM trajectory during walking circulation. This research then extracts velocity, acceleration and ground reverse force variation from gaits, and compare their transformation under different initial conditions. Finally, The study concludes discrepancies and similarities between the spring-mass walking model and human evolution behavior. The study will provide insights into bipedal explanation for evolution tendency and existing problems.

2. Related Works

2.1. Model Parameters Description

Here are several parameters used to illustrate walking trajectory and other information.

Table 1. Fundemental parameters of spring-mass model

Parameters	meaning
CM	Center of mass
x	Horizontal position of CM
x_dot	Horizontal accelaration of CM
y	Vertical position of CM
y_dot	Vertical acceleration of CM
GRF	Ground reaction force
g	Gravity constant
α_0	Angle of attack or touch-down angle of the leg(degree)
m	Body mass(kg)
L_0	Rest limb length(m)
E_total	System energy(J)
d	Distance of a complete stride(m)
W_k	The kinetic forward enrgy consumed during one stride
W_p	The potential gravitational energy consumed during one stride

2.2. Spring-Mass walking model

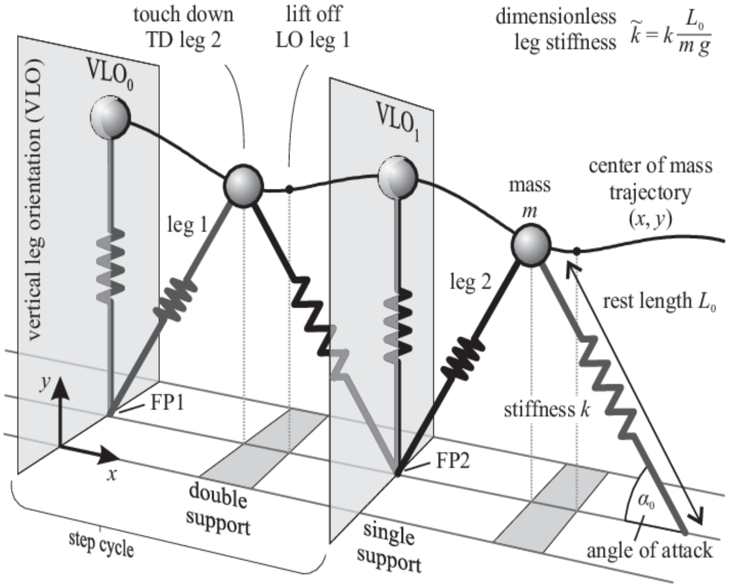

Figure 1. The bipedal spring–mass model for walking.[9]

This traditional bipedal walking model is designed by Geyer, which simulates truly human walking gesture better than typical reverse pendulum locomotion. This article regards the Spring-mass walking model as the foundation, and has done many calculations based on it.

Center of mass(CM) is supported by two equal rest length springs. Original horizontal velocity forces model walking in a compliant gait, meanwhile the circulation between gravitational petential energy and kinetic positive energy induces vertical CM locomotion. At the moment when the center of mass (CM) approaches its peak, the model is forced by gravity which acts directly through the line from the CM to the footpoint (FP1). Then swing-leg touches down the ground, its length still is rest length$l_0 = y/\sin\alpha_0$. CM decreases down then increases up during the time two legs stands on the ground. Leg 1 shortenes then lengthenes to its origin length, then pushes off from the ground. Spring energy powered by stiffness translates to kinetic energy and potential energy when spring lengthenes, this transition ends till leg 1 pushes off. It's worth to mention that during the periods from leg 2 touches down the ground to leg1 pushes off, FP1 stays in still. The walking model circulation is one step-to-step locomotion and a standard conceptual model, so walking model repeats the gaits aftewards.

In order to describe walking duration properly, Spring-mass walking model should be seperated to several period. While calculating ground reverse force, velocity and spring energy, walking phase is seperated to *double1*, *single*. While calculating physical equations, circulation is devided to *stance-single* and *stance-double* phases. *Stance double*, refers to the duration two legs all stand on the ground. *Stance single*, refers to the duration one leg stands on the ground.

2.3. The Evolution of Human Walking Gesture

During the evolution of hundred millions of years, for reasons like moving out of the trees, and trying to hunt in land, or walked long distance to search better survival environment, human walking gesture evolved to current kind. With the purpose to move in the relatively tiny place(e.g., arboreal locomotion), ancestors walked in curve gesture, which behaves lower CM displacement altough the muscle efficiency is also lower than normal gesture. Homo, the famous skeleton of our ancestor who approximately survived ~1.8 million years ago, showed straight-legged walking and relatively more CM movement, which is the evidence of human long distance migration. Other reaserch exploration remind scientists that human ancestors maybe already finished evolution before Homo[10][11]. After all, human ancestors evolved their leg skeleton and muscle construction, which improves muscle efficiency in faster

DOI: 10.54254/2755-2721/72/20241019

walking speed and increased CM displacement[12]. Modern human own better walking gesture that be adopt to various walking situation, e.g., flat, flexed or normal situation.

Compared to normal walking gestures, falt walking, i.e., humans control their walking gesture to minimize the CM displacement, could bring smaller vertical CM amplitude although muscle shrink-strech efficiency decreased as well. Flexed walking(i.e. walking in bouncy way), could increase muscle efficiency although CM displacement becomes larger, which means more gravitational potential energy consumed.

Due to better living conditions and unhealthy eating habits, the obesity rate is rapidly increasing in modern cities. This is leading to various injuries and illnesses. Obesity also has a noticeable effect on people's gaits. Those with higher BMIs tend to walk slower with shorter step lengths and wider step widths. If people become slim, they can improve their balance control strategies, and the amount of time spent in double-stance decreases.

It is strange that muscle efficiency decreases when walking on flat surfaces. Interestingly, this decrease in efficiency is not due to walking speed. In fact, efficiency actually increases during walking competitions. This is because competitors adopt an abnormal walking gesture in which they use their hips to generate force for moving forward, while keeping their legs as straight as possible, like a reverse pendulum, in order to gain faster speed. However, this gesture results in immense ground reverse force during competitions, which can be harmful to the knees and feet.

3. MATH

This part includes an equation for the simplified Spring-Mass walking model and a calculation for human walking parameters. Ordinary differential equations and trigonometric functions are used in mathematical explanation. In the standard conceptual model, CM is forced forward by ground reverse force(GRF), which directed from foot point at the ground r_{FP} to mass point CM; Gravitational force, the force always stright heading to the ground vertically; Spring elastic force, which generates by elastic deformation.

3.1. Spring-Mass Walking Model

$$\begin{cases} F_{xleft} = k\Delta x_{left} \times x/\sqrt{x^2+y^2} \\ F_{yleft} = k\Delta x_{left} \times y/\sqrt{x^2+y^2} \\ \Delta x_{left} = l_0 - \sqrt{x^2+y^2} \end{cases} \tag{1}$$

Where illustrates the locomotion of CM during initial left leg single stance.

$$\begin{cases} F_{xright} = k\Delta x_{right} \times (d-x)/\sqrt{(d-x)^2+y^2} \\ F_{yleft} = k\Delta x_{right} \times y/\sqrt{(d-x)^2+y^2} \\ \Delta x_{right} = l_0 - \sqrt{(d-x)^2+y^2} \end{cases} \tag{2}$$

Where illustrates the spring elastic force of right leg, especially given by distance of one stride d. Since original point is settled at left leg touch-down point.

$$\begin{cases} m\ddot{x} = Px \\ m\ddot{y} = Py - mg \\ P = k(l_0/\sqrt{x^2+y^2} - 1) \end{cases} \tag{3}$$

Where reproduce bipedal walking robot CM displacement in situation that left leg stands on the ground, while right leg swings in the air. The end condition of this period is right leg touched down the ground, which equated as $y = l_0 \sin \alpha_0$.

$$\begin{cases} m\ddot{x} = Px - Q(d-x) \\ m\ddot{y} = Py + Qy - mg \\ Q = k(l_0/\sqrt{(d-x)^2 + y^2} - 1) \end{cases} \tag{4}$$

Where calculate CM in *double-stance* duration. Obviously two spring legs both force CM to move, thus another constant Q is included to explain the complex equation. The end condition of this period is left leg puches off, which equated as $l_0 = \sqrt{x^2 + y^2}$.

$$\begin{cases} m\ddot{x} = -Q(d-x) \\ m\ddot{y} = Qy - mg \end{cases} \tag{5}$$

Where means the last periond within one circulation stride. The end condition of this period is $\ddot{y} = 0$.

3.2. Calculation of other Physical Parameters

Energy consumption and transition always matters in locomotion situation. Thus the calculation for all kinds of energy should take into account.

$$\begin{cases} E\_total = E_{spring} + mgy + E_k \\ E_k = m(\dot{x}^2 + \dot{y}^2)/2 \\ E_{spring} = k\Delta x^2/2 \\ E_{k\_forward} = m\dot{x}^2/2 \\ \varepsilon_{k\_forward} = W_{k\_forward}/E\_total \end{cases} \tag{6}$$

Where reveals equation for amount of model energy, and efficiency for kinetic energy and potential gravitational energy. Initial moving speed and CM posotion are also seen as primary parameters. Since $\dot{y} = 0$ in the beginning(peak moment), $E_total$could seen as constant during the specific circulation.

3.3. Simulation Analysis

Calculation for each situations includes 50 steps, the results plotted in figure are stablized gaits without interrupt abortion. The simulation model is implemented in MATLAB/SIMULINK (The MathWorks Inc., Natick, MA, USA). We use an integrated Runge–Kutta variable step integrator (ode45) with an absolute and relative error tolerance of 10^{-11}.

3.4. Algorithms

With parameters that exceed calculation boundary, model simulation would collapses. Collapse includes y_peak becomes higher than leg rest length, which means CM flies away from ground, or trejactory for n_steps is irregular. By ploting y_peak return map(fig.3), the trejactory congerges to one basin point reveals that model under these initial parameters are reasonable.

Algorithm 1: simulating model by ode45 function

Input: m: mass; l0:leg rest length; alpha0: touch-down degree; k: spring stiffness; n_steps: circulation times for simulation;{x,y}: CM initial position; {x_dot,y_dot}: CM initial speed

Output: {x_t,y_t}: CM position; {x_dot_t,y_dot_t}: CM speed;{GRF_x,GRF_y}: instantanuous GRF in vertical and horizontal direction; {x_ddot,y_ddot}: acceleration of CM; t: time to walk a entire stride

if i < n_steps and max{y_t}>$\boldsymbol{l_0}$ **then**

peak moment→touch-down moment

Single stance function→ode45
Foot_impact→ode45
{m,alpha0,k,l0}→{x_t,y_t ,x_ddot,y_ddot,t}
{x_t,y_t}→{x_dot,y_dot}

double stance→push off moment

Double stance function→ode45
Push off→ode45
{m,alpha0,k,l0}→{x_t,y_t ,x_ddot,y_ddot,t}
{x_t,y_t}→{x_dot,y_dot}

single stance→peak moment

Single stance function→ode45
Peak→ode45
{m,alpha0,k,l0}→{x_t,y_t ,x_ddot,y_ddot,t}
{x_t,y_t}→{x_dot,y_dot}

GRF calculation

{x_dot,y_dot,m}→{GRF_x,GRF_y}
{t,GRF_x,GRF_y}→plot

end if

Algorithm 2: y-peak return map

Input: {x_t,y_t}: instantanuous CM position; n_steps: circulation times for simulation

Output:{y_(t),y_(t+1)}: variation about peaks for each steps; plot for return map

If i < n_steps and max{y_t}>l_0 **then**

{x_t,y_t}→{y_(t)},y_(t+1)}

plot(y_(t+1) versus y_(t) **)**

end if

4. Result

4.1. Reproduction of longer leg and heavier average weight

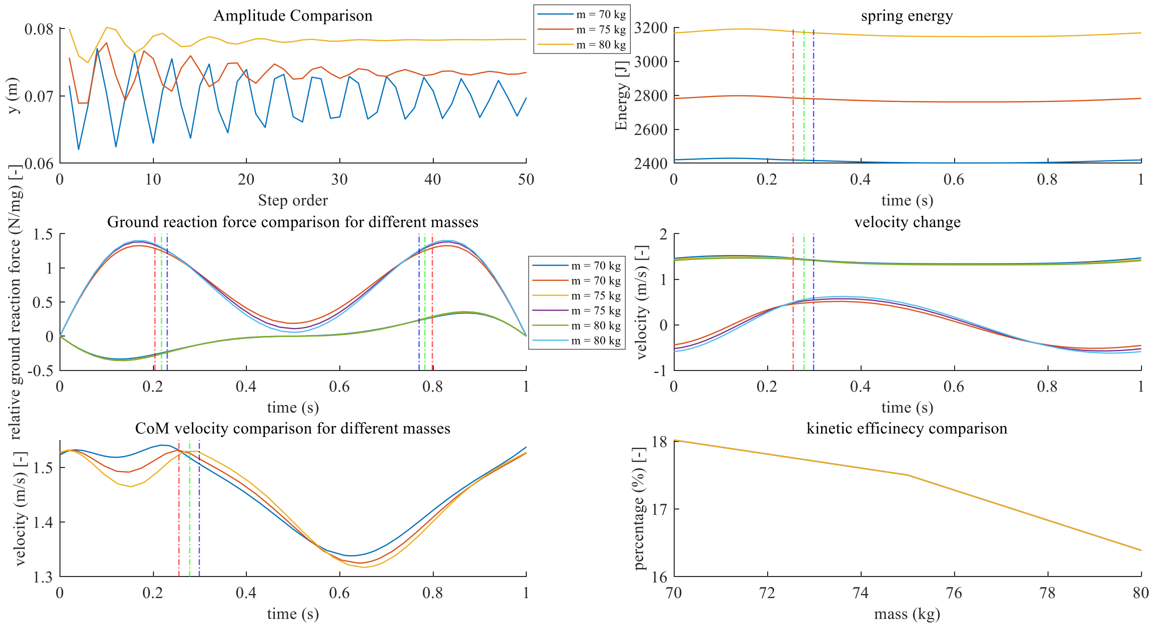

Figure 2. Comparison plots for different masses. First plot on top left position shows amplitude variation in 50 steps for different masses.(leg rest length: 1m, spring stiffness: 23000N/m, touch-down degree: 70 degree, initial forward walking speed: 1.3m/s) Top right plot shows the energy stored by compressed spring during double1-single periods. Dotted lines with red, green and blue colours means respective periods boundary, *i.e.*, the time leg1 pushes off from the ground or the time leg1 touches the ground. Time axis illustrates the CM moment among entire stride. GRF plot includes horizontal GRF and vertical GRF, each mass has both GRF, thus six lines are plotted for three masses. The labels column listed in the middle position labels lines for second lines, the rest plots' lines cater to labels column listed in the top middle position except kinetic efficiency comparison plot.

Human ancestors were 10% shorter than modern people[13]. Longer legs were envolved to be adopt to long distance migration, accompnied by heavier weight to support higher body. And model could simulate under same height, the several physical parametres for people in differnet weight. As y-return map shows in figure 3, Spring-mass walking model could work stably under $mass = 70{\sim}80kg$ ($k = 23000Nm^{-1}$, $alpha0 = 70°, l_0 = 1m$). In figure 2, stable and average larger amplitude occurs in $mass = 80kg$, conversely $mass = 70kg$could see unstable and average smaller amplitude. Spring energy increases when mass increases. Low mass as $70kg$ refers to ape, spring energy peaks to $2429.43J$ before double1 period finishes. At the same time(lighter weight), kinetic efficiency decreased. For $mass = 70kg$, kinetic efficiency is18.01%, this parameter decreased to 16.39% when $mass = 80kg$. With mass increases, heavy model has larger vertical GRF amplitude. Situation is similar when comes to horizontal GRF. Model with lighter mass reaches periods boundary faster, and walks in faster CM speed, CM reaches double1-single boundary at 25.4% of whole period time, and peaks to 1.541 then decreased to 1.338. $Mass = 80kg$, CM reaches double1-single boundary at 1.528 then decreased to 1.317. All masses reaches peak before push off then decreases to minimum during single period, but lighter mass meets boundary of double1-single faster.

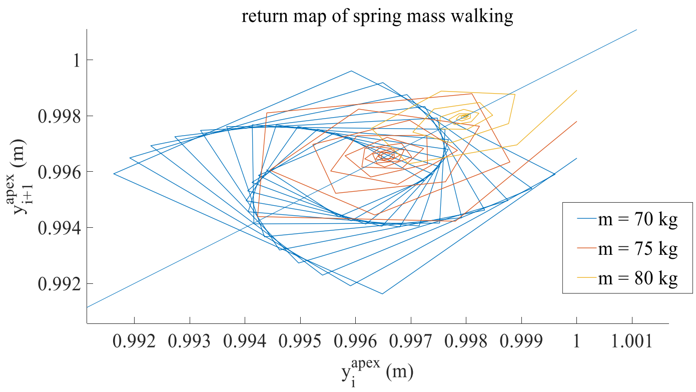

Figure 3. comparison between y_i^{apex} and y_{i+1}^{apex}, i.e., in stride i, the peak vertical CM position is y_i^{apex}, in this comparison time, y_i^{apex} is data in y axies, then it becomes data in x axies in next comparason time, means y_{i+1}^{apex} versus y_i^{apex}.

Spring-mass walking model could work stably under l_0 =0.93m~1.01m(m=70kg, $k = 23000Nm^{-1}$,$alpha0 = 70°$). In figure 4, stable and average larger amplitude occurs in $l_0 = 0.93m$, conversely $l_0 = 1.01m$could see unstable and average smaller amplitude. Before leg length increases to 1.00m, Spring energy decreases when length increases. Shorter leg length like 0.93m refers to ape. After leg length reaches 1.00m, walking model shows tendency to collapse, and has converse behaviour compared to leg length that shorter than 1.00m. The major difference appears in high spring energy region. Kinetic efficiency increased when leg lengthens. All masses reaches peak before push off then decreases to minimum during single period. Under these initial parameter, leg length l_0 influences behaviors of CM conversely before and after l_0 = 1m.

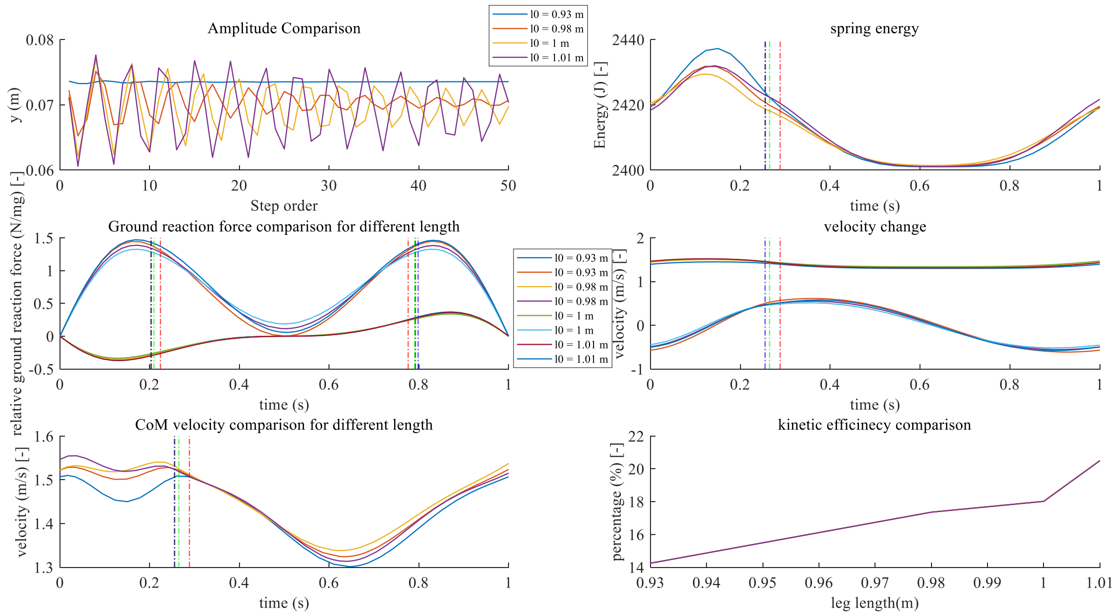

Figure 4. Comparison plots for different leg rest lengths.

4.2. Reproduction of leg skeletal structure

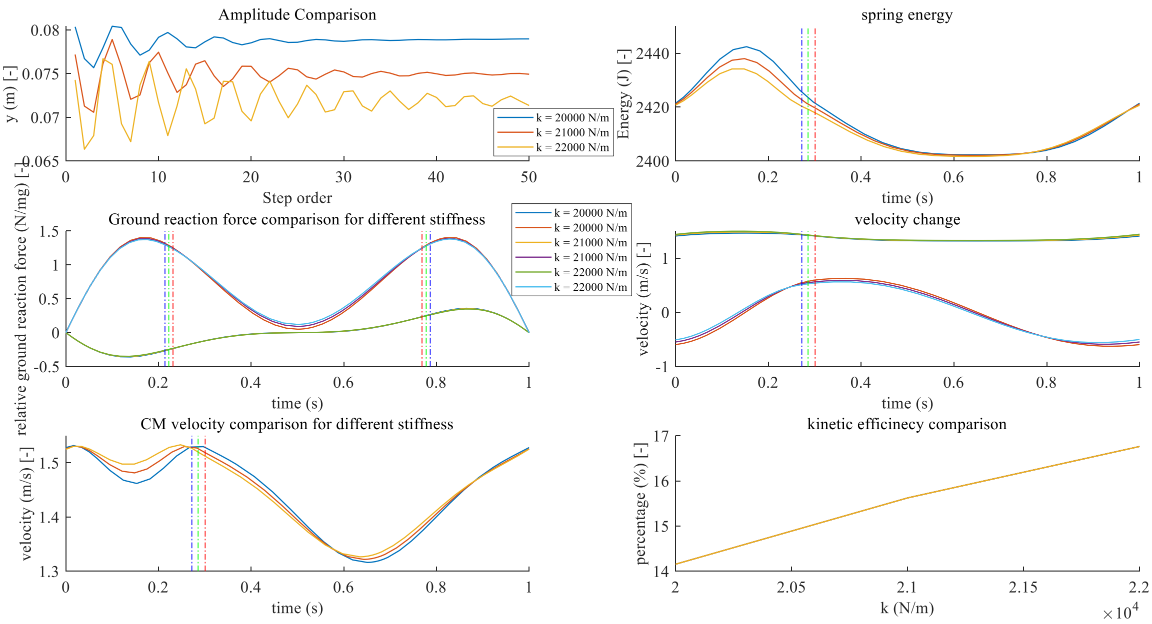

Figure 5. Comparison plots for different stiffnesses.

Huamn evolution includes legs more straight, this procedure could reproduce by changing spring stiffness and touch-down degree.

Spring-mass walking model could work stably under k = 20000Nm^{-1}~22000Nm^{-1} (m=70kg, *alpha0*=70°, l_0=1m). In figure 5, stable and average larger amplitude approximately 0.079m occurs in k=20000Nm^{-1}, conversely k=22000Nm^{-1} could see unstable and average smaller amplitude to 0.072m. Spring energy decreases when mass increases. Lower spring stiffness refers to ancestors. In figure 5, spring energy peaks to 2442.42J before *double1* period finishes. At the same time(lower stiffness), kinetic efficiency decreased. With stiffness extent increases, model has samller vertical GRF amplitude. Situation changes when it comes to horizontal GRF, as could see that three different stiffness shows nearly same amplitude. Model has harder spring stiffness reaches periods boundary faster, and walks in faster CM speed. All masses reaches peak before push off then decreases to minimum during single period, but model with harder spring stiffness meets boundary of double1-single faster.

Spring-mass walking model could work stably under *alpha0*= 70° − 72°.(m=70kg,k=23000Nm^{-1} ,l_0= 1m). In figure 6, stable and average smaller amplitude occurs in *alpha0* =72°, conversely *alpha0*=70° could see unstable and average larger amplitude. Less degree shows more spring energy before period boundary, then same degree conversely shows less spring energy when model enters single period, spring energy peaks to 2435.71J before *double1* period finishes.When *alpha0* becomes larger, kinetic efficiency decreased. Situation changes when it comes to horizontal GRF, as could see that three different stiffness shows nearly same amplitude. Model has smaller *alpha0* reaches periods boundary faster, and walks in faster CM speed. All masses reaches peak before push off then decreases to minimum during single period, but smaller degree meets boundary of *double1-single* faster.

DOI: 10.54254/2755-2721/72/20241019

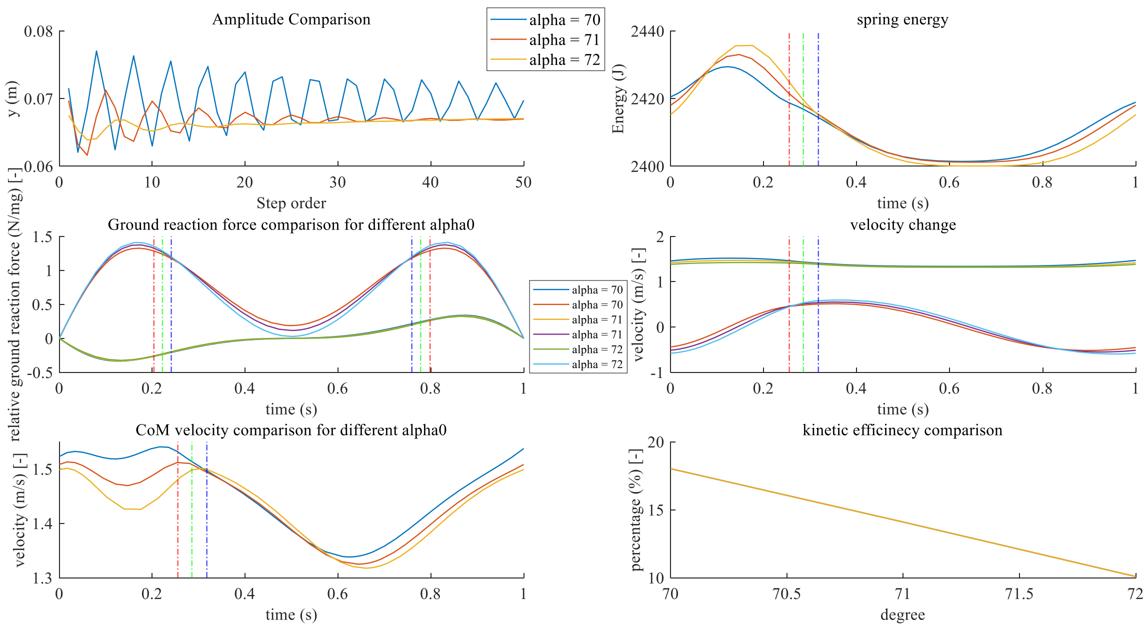

Figure 6. Comparison plots for different touch-down $alpha0$.

5. Discussion

Compared to the pendulum-like walking model, which has straight legs, Spring-mass walking model owns two equal rest length spring legs, which store gravitational potential energy during walking period. Aim to walk long distance migration and hunt on the land, human ancestors evolved long ratio legs, thus muscle in legs becomes stronger to support body, accompanied by smaller touch-down angle. If touch-down angle becomes larger as legs being longer, effort spent on forward walking is to huge that can't maintain long time walking. By settling different independent variation, this part concludes some similarity and deviation between human walking and spring-mass walking robots.

5.1. Similarity between Human and Spring-mass Robots

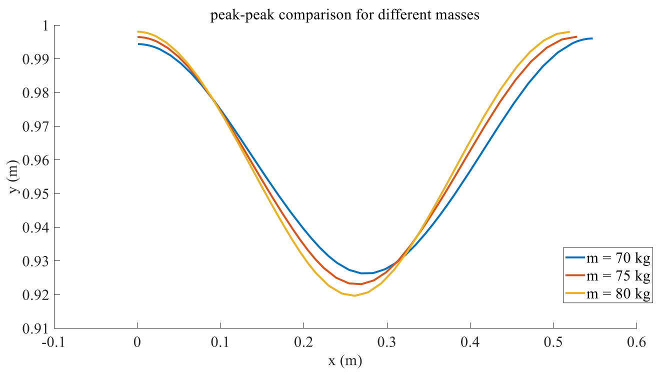

Figure 7. the comparison about peak(maximum y position of CM) to peak with different masses. The simulation starts at peak time for i th gait, then experiences double stance and ends at peak for $i+1$ th gait.

According to the figures and graphs, the efficiency of forward movement increases when the legs become more prolonged, and the spring stiffness becomes larger. This result caters the existing result, which proves reasonability for the simulation[14]. If the spring is soft, it is similar to having weak legs, which can cause a person to fall down easily, as shown by the amplitude graph. As shown in the figure, the variation of spring stiffness has a tiny influence on GRF since the settled mass is constant. In a single stance, kinetic and spring energy initially transform into gravitational potential energy, then convert back when vertical CM displacement decreases. Under the same mass, touch-down degree and spring stiffness, the forward kinetic efficiency shows same results in spring-mass walking model when legs becomes longer. Human ancestors evolved longer legs to walk efficienctly, spring-mass model could prove the reasonability to the conclusion. The amplitude of spring-mass model shows obvious sensitivity to variable leg lengths. Model compensates the stability of gaits for efficient forward kinetic moving transition. Longer legs should owns faster speed, as higher human could walk faster than shorter people. Shorter legs transforms more kinetic energy to spring energy.

The stability of the spring-mass walking model is also sensitive to the variation of masses. Heavier model could stablizes its amplitude to one constant quickly, lighter model easily flies away and breaks the simulation if initial mass being small enough. People with higher BMI walked slower with shorter step lengths, wider step widths, and longer double support times. Walking model with heavier mass has smaller gait and larger vertical CM displacement, and supports the idea that adult with higher BMI spends more time in one whole gait for double stance period. Need to mention here, variation mass here is an independent parameter, instead of dependent variation changes by leg length. After checking the return map, the model collapses easily if set both leg length and mass as independent variations.

5.2. Difference between Human and Spring-mass Robots

After all, spring-mass model has many oversimplification compared to truly human walking gesture, thus some differences happens in simulation. Robots with larger touch-down degree shows different results with our expectation.

The stability of spring-mass walking model is sensitive to the variation of touch-down degree. Human walks in small touch-down degree must steps out large. In forward speed angle, that is reasonable for faster speed. In muscle angle, hip joint suffers larger compression and requires more force to step out one big step. And the result in figure 6 shows that larger step(i.e., smaller touch-down angle) brings lower spring energy for model.

6. Conclusion

Human ancestors adapted to ground hunting and migration by lengthening their legs and strengthening their leg muscles. The model proves that these changes increase the efficiency of forward movement. Compared to normal walking, which decreases its touch-down degree to gain faster speed and larger CM displacement, flat walking(i.e., larger touch-down degree) compensates its forward moving efficiency and distance per step to gain smaller vertical CM amplitude, accompanied by larger vertical CM amplitude and slower walking speed. Flat walking also could explained as translating more gravitational potential energy to compressed leg energy, rather than body moving velocity,(i.e., brings larger vertical GRF and smaller horizontal GRF). That explains the decrease in forward kinetic efficiency, which proves existing findings in another dimension[15].

People who suffer from high BMI put more effort than normal people to walk and easily lose balance. Conclusion proves this opinion that they must spend more time in double stance, and compress larger momentum to change vertical CM speed direction, the latter result also means heavier burden for knees and waist. According to existing results, individuals with higher body weight should consider walking with a curved leg stance and taking longer strides to reduce the pressure on their knees. It is recommended that they engage in exercises to strengthen their leg muscles, as this not only improves their walking speed but also reduces the burden on their knees and waist from excessive loading.

The simplified model used for studying bipedal locomotion does not consider the human body's inner effort, such as metabolic energy. Therefore, conclusions and explanations are based solely on the energy generated and translated against outer forces. However, a more sophisticated model, as proposed by Hu Di[16], can better simulate the delicate structure of the human foot and provide a different perspective on the evolution of bipedalism in terms of moment. Despite this model's improvements, the deeper reasons behind the evolution of bipedalism are still unsolved and require further research beyond this traditional but straightforward model.

References

[1] Alexander R M , Jayes A S .Vertical movements in walking and running[J].Journal of Zoology, 2010, 185(1):27-40.DOI:10.1111/j.1469-7998.1978.tb03311.x.

[2] Schmitt D .Insights into the evolution of human bipedalism from experimental studies of humans and other primates[J].The Journal of experimental biology, 2003, 206(Pt 9):1437.DOI:10.1242/jeb.00279.

[3] Kim D , Gill S V .Changes in center of pressure velocities during obstacle crossing one year after bariatric surgery.[J].Elsevier, 2020.DOI:10.1016/j.gaitpost.2019.12.020.

[4] F. Iida, J. Rummel, and A. Seyfarth, “Bipedal walking and running with compliant legs,” in Proc. IEEE Int. Conf. Robotics and Automation, Roma, Italy, 2007, pp. 3970–3975.

[5] Geyer H , Seyfarth A , Blickhan R .Compliant leg behaviour explains basic dynamics of walking and running[J].Proceedings of the Royal Society B: Biological Sciences, 2006, 273(1603):2861-2867.DOI:10.1098/rspb.2006.3637.

[6] Goslow T , Bennet A F , Blickhan R ,et al.How are locomotor systems integrated and how have evolutionary innovations been introduced?[J].Complex organismal functions: integration and evolution in vertebrates. 1989.

[7] Mcmahon T A , Cheng G C .The mechanics of running: how does stiffness couple with speed?[J].Journal of Biomechanics, 1990, 23(supp-S1):65-78.DOI:10.1016/0021-9290(90)90042-2.

[8] M. d. Lasa and M. Buehler, “Dynamic compliant quadruped walking,” in Proc. IEEE Int. Conf. Robotics and Automation, Seoul, Korea, 2001, pp. 3153–3158.

[9] Rummel J , Blum Y , Seyfarth A .Robust and efficient walking with spring-like legs[J].Bioinspiration & Biomimetics, 2010, 5(4):046004.DOI:10.1088/1748-3182/5/4/046004.

[10] Nagano A,Umberger B R,Marzke M W.Neuromusculoskeletal computer modeling and simulation of upright, straight-legged, bipedal locomotion of Australopithecus afarensis (A.L. 288-1)[J].American Journal of Physical Anthropology, 2005, 126(1):2-13.DOI:10.1002/ajpa.10408.

[11] William,I,Sellers,et al.Stride lengths, speed and energy costs in walking of Australopithecus afarensis: using evolutionary robotics to predict locomotion of early human ancestors[J].Journal of the Royal Society Interface, 2005.DOI:10.1098/rsif.2005.0060.

[12] C. R. Lee and C. T. Farley, “Determinants of the center of mass trajectory in human walking and running,” J. Exp. Biol., vol. 201, no. 21, pp. 2935–2944, 1998.

[13] Stulp G , Barrett L .Evolutionary perspectives on human height variation[J]. Biological Reviews, 2016.DOI:10.1111/brv.12165.

[14] M. Srinivasan and A. Ruina, “Computer optimization of a minimal biped model discovers walking and running,” Nature, vol. 439, no. 7072, pp. 72–75, 2006.

[15] Massaad F , Lejeune T M , Detrembleur C .The up and down bobbing of human walking: a compromise between muscle work and efficiency.[J]. The Journal of Physiology, 2007, 582(Pt 2):789-799.DOI:10.1113/jphysiol.2007.127969.

[16] Hu Di , Xiong C H , Sun R .Working out the bipedal walking expenditure of energy based on foot morphology of different hominid genera: implications for foot evolution[J].Journal of Theoretical Biology, 2021:110646.DOI:10.1016/j.jtbi.2021.110646.