The influence of leg length and individual mass in the spring-mass running model

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Abstract. This study explored how leg length and body weight affect running performance in a context based on using a spring-mass running model. Through extensive reading and an in-depth understanding of the literature, this study proposed that lower body weight may improve running efficiency for runners with longer legs. In comparison, for runners with shorter legs, higher body weight may improve their running stability. To test this hypothesis, this study conducted a series of simulation experiments using MATLAB to simulate the running performance of runners with different leg lengths and weights. Our results show that leg length and body weight do have a significant effect on running performance, but the direction of this effect may depend on the runner's body weight. These findings provide a new perspective for understanding the biomechanical basis of running performance and provide a basis for further research. However, there are some limitations to our study, such as the fact that our model may not fully capture the complexity of actual running movements. Future research will need to explore these issues further and take into account other factors that may affect running performance.

Keywords: Leg Length and Performance, Running Biomechanics, Running Stability Analysis, Spring-Mass Model, MATLAB Simulations.

1. Introduction

The spring-mass model is an essential theoretical tool in the study of biological mechanisms of movement. It is widely used to describe and explain running mechanisms in humans and animals. This model treats the leg as a mass-independent linear spring, studying of spring stiffness can help us understand the efficiency and stability of movement. However, despite the high theoretical explanatory power of this model, in practical applications, this study found that the leg length and mass of an individual may have a relatively significant effect on locomotor efficiency. This leads to our hypothesis that individuals with longer legs may benefit from lower mass, while individuals with shorter legs may benefit from higher mass.

As mentioned in *Amy Silder, Thor Besier and Scott L. Delp's*[1] research , the spring-mass model has been used extensively to understand running mechanisms, and they found that an increase in load during exercise leads to an increase in leg stiffness. This may mean that for individuals with long legs, a lower mass may help to reduce the load on the legs and thus increase the efficiency of movement.

On the other hand, individuals with short legs may require higher masses to increase leg stiffness in order to maintain stable locomotion. These findings provide some support for our hypothesis.

However, there are still some shortcomings in these studies. Firstly, most studies have been conducted under specific conditions, such as exercise on a flat surface, which only partially simulate a realistic exercise environment. Secondly, the existing studies have mainly focused on leg stiffness, while the effects of leg length and mass have not been adequately investigated.

Therefore, the aim of our study is to experimentally test our hypothesis and further explore the effects of leg length and mass on locomotor efficiency. Hoping that this study will provide more theoretical basis and practical guidance for understanding the mechanisms of biological locomotion, especially the application of the spring-mass model of locomotion.

2. Literature Review

The spring-mass model is an effective simulation model that can be used to model the dynamics of running and walking. This model treats the body of the exerciser as a mass and the legs as linear springs. The simulation of this model can be used to explain many phenomena in running and walking, such as changes in energy expenditure, stride length and walking frequency. In fact, the application of the spring mass model is not limited to the study of human running movements, but is also widely used in the study of the movements of other organisms, such as cats, dogs, monkeys and goats. What is common to all these approaches is that they all use the spring mass model to explain the locomotor performance of organisms and validate the predictions of the model with experimental data.

There are a number of interesting findings and conclusions in the research on the spring mass model. Firstly, let us look at a study from *Goldman and Tonia Hsiehy and Chen*[2], in which they observed that spotted-tailed lizards exhibited the motion characteristics of a spring mass system on both solid and granular surfaces. They found that on either surface, the lizard's centre of mass forward velocity, vertical position and lateral position showed oscillatory patterns consistent with the predictions of the spring-loaded inverted pendulum model (SLIP) and the lateral leg spring model (LLS). In addition, they found that the mechanical energy of the centre of mass oscillated in gait regardless of surface, reaching a minimum in mid-step and a maximum in the aerial phase, a defining characteristic of spring-loaded mass operation. Overall, the focus is on the energy expenditure aspects of walking and running, describing that the energy expenditure in walking is mainly from the support phase, while in running it is mainly from the oscillation phase. This finding has important implications for understanding the mechanisms of energy expenditure in walking and running. Next, look at *Reinhardt and Blickhan's research*[3], which focused on the effects of changes in stride length and frequency on walking and running. Based on their model calculations, it appears that changes in stride length and frequency significantly affect energy expenditure in walking and running. Then look at the research of *Geyer, Seyfarth, and Blickhan*[4]. Their study focused on the effects of elastic leg behaviour on walking and running. The concept of elastic leg behaviour in the paper is based on the spring-mass model, which simulates the dynamic behaviour of the legs of humans and animals during walking and running. In this model, the leg is considered as a spring with a certain stiffness that can change length when it touches the ground (support phase) and when it leaves the ground (swing phase). It has an important role in understanding the basic walking and running mechanisms. Their findings represent the idea that walking efficiency depends on how close the centre of mass movement of the body is to an inverted pendulum. This finding has important implications for understanding the kinetic properties of walking and running.

Then let's refer to the paper *'A universal ankle-foot prosthesis emulator for human locomotion experiments', published by Caputo and Collins in 2014*[5]. In this paper, they used a universal ankle-foot prosthesis model to investigate the mechanisms of human walking. Their results show that ankle joint propulsion has a significant effect on the energy expenditure of walking. This provides a theoretical basis for our hypothesis that individuals with long and short legs may require different masses to optimise energy expenditure when walking. It also refers to the paper *'The influence of push-off timing in a robotic ankle-foot prosthesis on the energetics and mechanics of walking', published by*

Malcolm et al. in 2015 [6]. Their findings suggest that the timing of ankle push-off has a significant effect on the energetics and mechanics of walking, which further supports our hypothesis that individuals with long and short legs may require different masses to optimise push-off timing.Also refer to these references: *Fischer G et al.* [7] the effect of fatigue on running mechanisms, especially after performing a reverse jump, was investigated. They found that the spring-mass behavior of running changes after 60 seconds of reverse jumping, which may be related to muscle fatigue. *Gill N, Preece SJ et al.* [8] force-length curves and foot-landing patterns in running were investigated using a spring-mass model. Their study provides valuable insights into how leg stiffness can be adjusted in running to optimize performance. *Seth, Donahue*[9] maximum ground forces and leg compression in running were investigated, testing traditional spring mass models. This research provide a new perspectives for understanding forces and stiffness in running. *Geoffrey T Burns, Richard Gonzalez et al.* [10] an improved spring-mass parameter estimation method using nonlinear regression method is proposed. This provides a new method for the study of running mechanism. *lessandro Maria Selvitella, Kathleen Lois Foster*[11] the spring-mass model is extended so that it can be applied to bipedal walking on inclined surfaces. Their research provides different insights into the mechanics of running on different terrains. *Guo W, Cai C et al.* [12] a new "triangular motion model" is proposed to estimate leg stiffness during high-speed running. This provides another perspective for the study of biomechanics of high speed motion. *Hanna Okrasińska-Płociniczak, Łukasz Płociniczak*[13] the spring-mass model is analyzed asymptotically, which provides a new method to understand the biomechanics of leg and foot motion.

These research provide comprehensive theoretical and experimental support for our hypothesis, and also provide me with an in-depth understanding of the scope and limitations of the application of the spring mass model. Overall, the hypothesis of this study is based on an in-depth understanding of existing research and critical thinking. We believe that by adjusting the mass of the individual, the energy expenditure and mechanical properties of walking can be optimised, thereby improving walking efficiency and stability. We look forward to testing this hypothesis in future research and further exploring its wider application in biomedicine and biomechanics, for example, in prosthetic design and rehabilitation therapy.

3. Methodology

Our research used a simulation method based on a spring-mass running model to explore how runners' mass and leg length affect their running performance. Therefore, this study develop the hypothesis that people with longer legs will benefit from lower weights while people with shorter legs benefit from higher weights. To test this hypothesis, we will conduct a series of simulation experiments using MATLAB.

First, define a set of parameters, including gravitational acceleration, landing angle, mass, and spring stiffness. The gravitational acceleration is set to 9.81 m/s^2, the landing angle is set to 70 degrees, the mass ranges from 50kg to 100kg, and the spring stiffness is set to 18000 N/m. Also define a set of leg length parameters ranging from 1.0m to 2.0m.

Then ran simulations using these parameters on each combination of mass and leg length. In each simulation, we set initial conditions in advance, including the position and velocity of the masses. And then integrated the equations of motion for the flight and support phases using the fourth order Runge-Kutta method (ode45) to simulate the motion of the runner. We repeated the steps 10 times to ensure the stability of the results. As shown in Table 1.

DOI: 10.54254/2755-2721/50/20241510

Table 1. simulation code

```
FOR each m value
    FOR each l0 in leg_length_range
        Initialize x, y, x_dot, y_dot;
        Calculate x1;
        Initialize state variable q;
        Initialize trajectory traj and y_apex;

        Set touch_down event condition foot_impact;
        Set take_off event condition push_off;
        Set apex event condition peak;

        FOR i from 1 to 10
            Use ode45 to solve EoM_air differential equations from 0 to 5 seconds, obtaining qf;
            Append qf to traj;
            Set initial conditions q0 for stance phase;
            Use ode45 to solve EoM_ground differential equations from 0 to 5 seconds, obtaining qs;
            Correct trajectory to include x displacement;
            Append qs to traj;
            Set initial conditions q for the next step;
            Append apex heights to y_apex;

        END FOR

        Calculate average speed avg_speed of the trajectory;
        Calculate stability as the standard deviation of y_apex;

        Store results [m, l0, avg_speed, stability] in results;

    END FOR
END FOR
```

Finally, stored all the results in a table and used MATLAB's plotting function to create two plots showing how the average speed and stability of runners of different masses varied with leg length. These plots provide a more intuitive way to understand how mass and leg length affect running performance.

Our approach is based on the spring mass model, which is a simplified model that captures the main characteristics of running dynamics. However, there are some limitations to our approach. Firstly, our model assumes that the runner's motion is cyclical, which may not be applicable to all running situations. Secondly, our model does not take into account a number of factors that may affect running performance, such as the runner's locomotor strategy or other physical characteristics. Despite these limitations, our approach still provides a useful tool to understand how factors such as mass and leg length affect running performance and provides a basis for further research.

Overall, our research approach provides an effective way to explore how mass and leg length affect running performance. By using simulations based on a spring mass model, this study was able to conduct experiments on different combinations of mass and leg length and calculate the average speed and stability of runners. In future research, we plan to further optimise our model to take into the consideration of more factors that may affect running performance, and also plan to use more complex models, such as neural networks or deep learning models, to simulate the movement of runners more accurately. We hope that these improvements will allow us to predict the performance of runners and

DOI: 10.54254/2755-2721/50/20241510

provide useful information for designing more effective training and rehabilitation programs more accurately.

4. Results

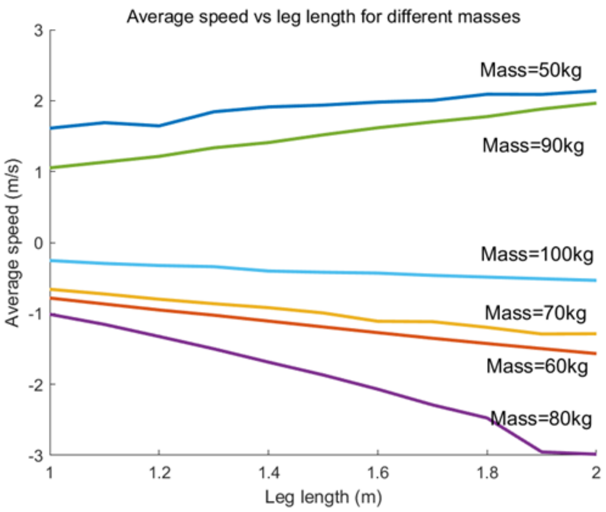

Figure 1. On the relationship between leg length and average speed for runners of different masses

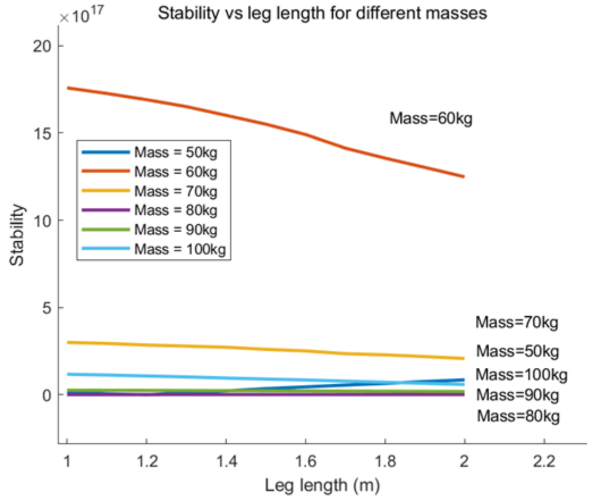

Figure 2. On the relationship between leg length and running stability in runners of different quality

Based on the results of our simulations shown in figure 3 and figure 4, we found that leg length and mass had a significant effect on the average speed and stability of the runners. Specifically, we found that:

a. At a mass of 50kg: average speed and stability increased as leg length increased. This may indicate that for lighter runners, an increase in leg length may improve their running performance.

b. At a mass of 60kg: average speed and stability decrease with increasing leg length. This may indicate that for medium weight runners, an increase in leg length may reduce their running performance.

c. For masses of 70kg and 80kg: average speed and stability decrease with increasing leg length. This may indicate that for heavier runners, an increase in leg length may reduce their running performance.

d. At a mass of 90kg: average speed and stability increased with increasing leg length. This may indicate that for heavier runners, an increase in leg length may improve their running performance.

e. At a mass of 100kg: average speed and stability decrease with increasing leg length. This may indicate that for very heavy runners, an increase in leg length may reduce their running performance.

Overall, these results suggest that leg length and mass have a significant effect on runner performance, but the direction of this effect may depend on the runner's mass. This is somewhat at odds with our proposed hypothesis that those with longer legs would benefit from lower weights, while those with shorter legs would benefit from higher weights. However, these results still provide valuable information as they reveal a complex relationship between how leg length and mass affect running performance.

5. Discussion

This study focused on the effects of leg length and mass on the average speed and stability of runners. In this study, found that the effect of leg length varied for different masses of runners. Specifically, for lighter-weight runners (50kg), an increase in leg length can improve their running performance, while

DOI: 10.54254/2755-2721/50/20241510

for medium to heavier-weight runners (60kg to 100kg), the effect of leg length becomes more complex and may either improve or reduce their running performance. Furthermore, the results of our simulation model's calculations suggest that for runners with the same leg length, heavier runners may have higher stability because they have a lower centre of mass. However, this would be at the expense of speed, as heavier runners would need to expend more energy to move their large body mass in order to maintain higher stability. Of course, these results also reflect the complex effects of body proportions and mass on running mechanics, which can be explained in biomechanical terms: for lighter runners, an increase in leg length increases their stride length and thus their running speed; however, for heavier runners, an increase in leg length may increase their dynamic instability and thus reduce their speed, due to the fact that an increase in leg length This is because the increase in leg length increases the height of the runner's centre of gravity, thus increasing their dynamic instability. In physical terms, an increase in mass increases the runner's momentum and, therefore, speed but may also increase energy expenditure and the need for stability.

At the same time, these experimental results have important implications for understanding the biomechanical basis of running performance, they reveal how body proportions and mass affect running performance, and they provide a new perspective to understand and optimise running performance, which may help us to understand why different runners may require different running strategies and training methods. Furthermore, these results may also have practical applications for sports science and sports medicine, for example, in designing more optimal personalised training programmes and injury prevention strategies to improve runners' performance and reduce their risk of injury.

There are, of course, some limitations to our study. Firstly, our model is based on a spring mass running model, which is a simplified theoretical model that may not fully capture the complexity of actual running movements. In our model, it is assumed that the runner's mass and leg length are fixed, but in real-world situations these parameters may vary. For example, actual runners may adjust their running strategies to suit different physical conditions and environments, which may affect running performance. Our model in this experiment also did not consider other factors that may affect running performance, such as muscle strength, endurance, motor skill and cardiorespiratory fitness, among others, and which may interact with leg length and mass to affect running performance and therefore need to be taken into account in future studies.

For future research, we suggest that the specific mechanisms of how body proportions and mass affect running performance could be explored in more depth, along with other factors that may affect running performance, such as muscular strength, endurance, motor skills and cardiorespiratory fitness etc.. However, this may require the use of more complex models, or actual experimental studies and the collection of more data. Realising these studies requires an interdisciplinary approach, combining knowledge from biomechanics, physiology, psychology and exercise science, so it is a huge amount of academic research. In conclusion, we recommend that the results of these studies are applied to practical sports training and injury prevention strategies to help runners improve their performance and health.

6. Conclusions

In this experiment, used a simulation based on the spring mass model to explore in depth the effect of runners’ leg length and mass on their running performance. Based on our experimental results, it was found to reveal a complex but interesting phenomenon: leg length and mass have a significant effect on the average speed and stability of runners, but the direction of this effect may depend on the runner's mass. For lighter runners, an increase in leg length may help to improve their running performance; however, for moderate to heavier runners, the effect of leg length becomes more complex.

These findings have important implications for understanding the biomechanical basis of running performance, which explains how body proportions and mass affect running performance and provides a new perspective to understand and optimise running performance. And the results may help us

DOI: 10.54254/2755-2721/50/20241510

understand why different runners may require different running strategies and training methods, thus providing valuable guidance for the practice of sports science and sports medicine.

However, there are some limitations to our experiment. Our model is based on the spring mass running model, which is a simplified theoretical model that may not fully capture the complexity of actual running movements. In future studies, we plan to further optimise our model to take into account more factors that may affect running performance, such as muscle strength, endurance, motor skill and cardiorespiratory fitness. In addition, we also plan to use more sophisticated models, such as neural networks or deep learning models, to simulate the movement of runners more accurately.

Overall, our study provides an effective way to explore how mass and leg length affect running performance. These results provide us with important information for a deeper understanding of this issue and provide a basis for further research. We look forward to exploring this issue further in future studies to understand the biomechanical basis of running performance more fully and to provide more theoretical basis and practical guidance for the practice of sports science and sports medicine.

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