

A Computational Simulation of Running Stability: Using the Spring Mass Model to Explore the Interaction of Body Weight and Shoe Softness

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Abstract. Shoe softness is a crucial factor that influences people's performance, comfort and potential risk of injuries while running, and directly affects the stability of running gait. While people with different body weights choose shoes with different levels of softness, how exactly the relationship between body weight and shoe softness plays a role in running is relatively overlooked. This study presents a computational model to investigate how body weight and shoe softness interact to influence the gait of running using the Spring Mass Model. As in this model, human leg is regarded as a compressible spring that provides rebound against the ground to support running, spring stiffness (k) and body mass (m) were respectively used to reflect shoe softness and body weight. Two experimental rounds were conducted via a Matlab simulator to simulate motion trajectories when running. In Round 1 where m was held constant and k varied, the results showed that excessively soft shoes (low k) caused the running gait to collapse and excessively stiff shoes (high k) would potentially lead to unstable running with too much rebound. In Round 2 where k was held constant and m varied, the results showed that on shoes that were identically soft, lighter runners experienced uncontrolled bouncing and heavier runners were more likely to experience collapse in running. To conclude, for people with different body weights, it is crucial for them to consider shoe softness accordingly in order to facilitate comfort and avoid fatigue and injuries when running. This study demonstrates how computational methodology can be utilized to inform human locomotion as well as footwear design and the broad scheme of physical health. Necessity to tailor shoe softness to different individuals was also enlightened.

Keywords: Gait; Body Mass; Spring Stiffness; Running Stability.

1. Introduction

Running is an important gait in terms of how necessary and frequently used it is for humans to progress through their daily lives. It also helps facilitate general health by, for example, promoting cardiovascular activity and helping lose weight. Thus, it is crucial for running to be a sustainable experience, and it is of practical importance how to make running more stable and universally comfortable for people with different body weights. For the purpose of maintaining running, one important factor is shoe softness, as it directly affects the rebound when foot makes contact to the ground, which in turn, affects velocity, comfort, people's intention of continuing and how much physical energy is consumed while running. Shoe softness should vary amongst people with different body weights, as different body weights result in varied amount of pressure against the ground, and provide varied amount of burden to the knees. However, the precise recommended variation of shoe softness as to body weight is relatively understudied. Hence, the field needs to investigate the potential relationship between body weight and shoe softness while running.

Specifically, although it is intuitive that the relatively overweight ones are more likely to experience difficulty while running, people with lower body weights may also find running unstable due to inappropriate amount of rebound. This conference paper delves into how shoe softness needs to be adjusted relative to body weight in order to maintain the gait of running. Although it has been addressed that using computational methodologies such as artificial intelligence to investigate bipedal locomotion can be practically challenging (Iida et al., 2007), empirical research has indeed demonstrated the increasing feasibility of doing so by relying on more advanced technologies (e.g.,

Li et al., 2024) and numerical frameworks such as the Spring Mass Model (Geyer et al., 2005, Bullimore & Burn, 2007, Kashri et al., 2018). To implement the Spring Mass Model on the current project, it is to investigate how changes in body mass will lead to changes in spring stiffness, because shoe softness is a direct reflection of spring stiffness when legs are imagined as compressible springs. Despite simulating legs as unbendable springs, research study by Dalleau et al. (1998) that investigated the impact of spring stiffness in the Spring Mass Model indeed showed a significant relationship between spring stiffness and oxygen consumption during treadmill running. This implies that how stiff the legs are directly influence people's performances at running, and indicates the practical implications that the Spring Mass Model can contribute.

2. Related Work

The Spring Mass Model for running was introduced by Blickhan (1989) as a simplified imitation of humans' running motion. This model simulates the motion of running by regarding human body as a point mass and leg as a spring. Every time the spring leg makes contact to the ground it will be compressed, exerting elastic energy and causes the entire mass to bounce up in an angle. Once the spring leg makes contact to the ground again the whole process restarts. After a certain number of cycles, the trajectory formed by the motion of the centre of mass (CoM) can be used to emulate how a human's body travels during a stable running motion. Body mass and spring stiffness, the two variables of interest, are two determinants of stability of the trajectory and whether it will collapse. Although this model assumes the leg to be massless, neglects some physiological features such as neuromuscular control as well as the influence of air resistance, it still provides a universal and dynamic simulation for legged locomotion by successfully accounting for the essential parameters.

Intuitively, one with higher body weight presses against the ground harder when running, so they will need to coincide such pressure with faster rebound. Higher spring stiffness in the Spring Mass Model serves as a source of faster rebound when foot makes contact to the ground. As in reality, the amount of rebound is not solely dependent on shoe softness but also related to other factors such as shoe materials, for simplicity purposes this project will assume that higher shoe softness is constantly related to slower rebound due to greater compression, and is therefore, related to lower spring stiffness. Hence, it is hypothesized that 1) higher body weight requires shoes that are less soft and 2) lower body weight requires shoes that are softer in order to maintain the gait of running or make the gait of running more stable.

3. Methods

The Spring Mass Model offered a suitable simulation for this project because it possessed spring stiffness and body mass in the model, which respectively represented shoe softness and body weight. This model consists of a stance phase, during which the spring is compressing against the ground and makes the centre of mass (CoM) form an upward concave trajectory:

$$\dot{r} = r\dot{\varphi}^2 + \frac{k}{m}(l_0 - r) - g \sin\varphi$$

$$\ddot{\varphi} = -\frac{2}{r}\dot{r}\dot{\varphi} - \frac{g}{r}\cos\varphi$$

and a flight phase, during which the spring bounces up and brings the centre of mass into a downward concave trajectory in the air:

$$\ddot{x} = 0$$

$$\ddot{y} = -g$$

where x and y are the horizontal and the vertical position of the CoM, r represents leg length, \dot{r} and \ddot{r} respectively represent leg length compression velocity and acceleration, φ represents leg

angle relative to the vertical, $\dot{\varphi}$ and $\ddot{\varphi}$ respectively represent angular velocity and acceleration, l_0 is initial leg length, k is spring stiffness, m is body mass and g is the gravitational acceleration. Relating this model to the practical running motion (see Figure 1), it imitated the process of the foot making contact to the ground, pushing the body forward, leaving the ground and causing extension of the leg, and propelling the body upwards.

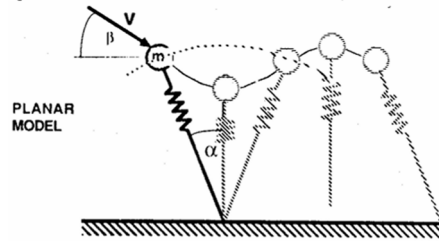


Figure 1. The Planar Model for Spring Mass Model (reproduced from Blickhan, 1989)

Specifically, different values of m and k were inserted into the model while all other parameters were held constant. The trajectories resulted from different sets of m and k values were simulated via a simulator created on Matlab (by Bio-Inspired Robotics Lab at University of Cambridge, 2020). If the simulation collapsed it meant the k value did not correspond with the m value. In other words, the simulation collapse would reflect that that certain shoe softness was not suitable at maintaining the gait of running when with that certain body weight.

Two rounds of parameter variation were conducted using the Matlab simulator (default parameters shown in Table 1). In Round 1, m was held constant at 80kg while k alternated between 20000N/m, 23000N/m and 26000N/m. By simulating the corresponding trajectories of CoM, it became assessable whether or not the running gait would collapse and which value of k would cause too much or too little rebound to support the motion. In Round 2, k was held constant at 23000N/m while m alternated between 60kg, 80kg and 100kg. Likewise, the trajectories of CoM would show which value of m elicited too much or too little pressure on the springy leg and caused running to collapse or be destabilized.

Table 1. The Initial Parameters of the Spring Mass Model Simulator.

Variable	m (kg)	l_0 (m)	k (N/m)	g	α_0 (deg)	x	y	\dot{x}	\dot{y}
	80	1	23000	9.81	70	0	1	5	0

Note. α_0 is angle of attack relative to the horizontal; \dot{x} and \dot{y} respectively represent the default horizontal and vertical velocity of the CoM

4. Results

As shown by results in Round 1 (see Figure 2) where m was held constant at 80kg, the motion trajectory of CoM collapsed when k was 20000N/m, indicating that this spring stiffness provided too little rebound for the body mass to support the gait of running. When k was 23000N/m, it took three cycles for the motion trajectory to find its pace and the vertical displacement oscillated between 0.88m and 0.96m, indicating a stable and well-controlled gait of running. When k was 26000N/m, the motion trajectory also stabilized after three cycles, but exhibited a highly steep and frequent oscillation, indicating excessive rebound from the ground. Hence, as higher shoe softness is related to lower leg stiffness, shoes that are too soft do not support the gait of running and shoes that are too stiff make the gait less controllable. In other words, as body weight increases or decreases, shoe softness also needs to be adjusted accordingly. Hypotheses 1 and 2 are supported.

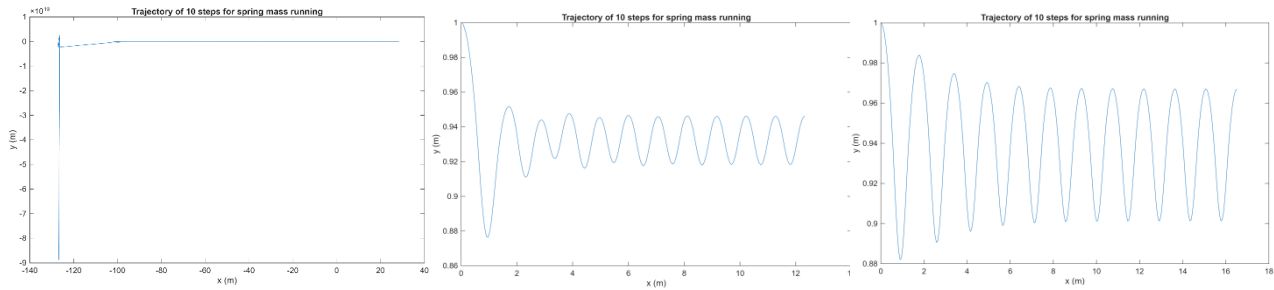


Figure 2. Trajectories of Motion of CoM during Round 1.

Note. From left to right are trajectories when $k = 20000\text{N/m}$, 23000N/m , 26000N/m while m was held constant at 80kg .

Results of Round 2 (see Figure 3) showed the motion trajectories where k was held constant at 23000N/m . When m was 60kg , the motion trajectory of CoM exhibited a continuously increasing pattern, suggesting that it failed to stabilize the gait of running and the motion could not be controlled. When m was 80kg , the motion trajectory was stable. When m was 100kg , the motion trajectory collapsed, indicating that too much pressure was elicited to the spring leg. These outcomes further indicate that people with different body weights need to pick their shoes accordingly.

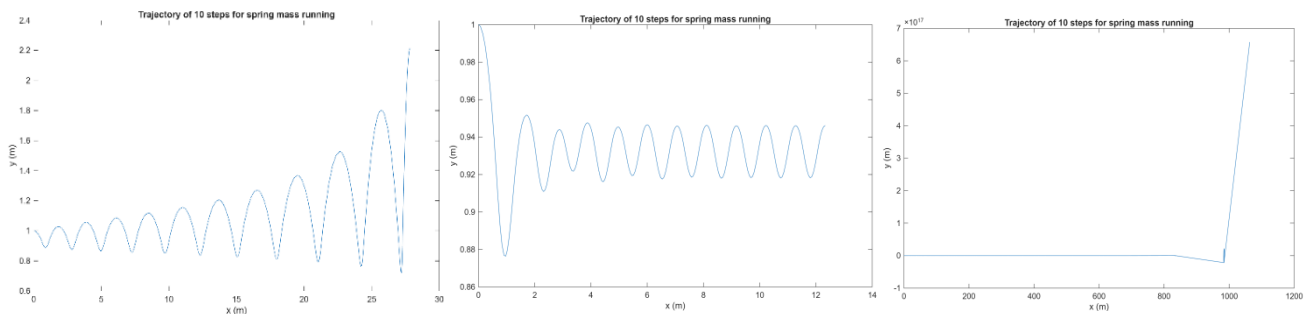


Figure 3. Trajectories of Motion of CoM during Round 2.

Note. From left to right are trajectories when $m = 60\text{kg}$, 80kg , 100kg while k was held constant at 23000N/m

5. Discussion

This study used the computationally simulated Spring Mass Model to examine the potential relationship between body weight and shoe softness in terms of how they determined the stability of the gait of running. In Round 1, the results indicated that shoes that are too soft can provide too little rebound to avoid the gait of running from collapsing. There is a limit of how much force human leg muscles can endure over time (Birn-Jeffery et al., 2014, van Poppel et al., 2021). As shoes that provide insufficient rebound are less able to help dissipate the force exerted towards the leg muscles when running, they simply cause each step to feel heavier than it should. An important implication is that with shoes that are too soft for one's body weight, their leg muscles will be more quickly exhausted due to accumulated force that exceeds the peak load, leading to fatigue or overuse injuries when running (van Poppel et al., 2021). On the other hand, results from Round 1 also indicated that shoes that are too stiff result in excessive rebound, and cause uncontrolled bouncing during the motion of running. Despite intuitively, shoes that are stiff or bouncy help unload the forces exerted to the leg muscles, shoes with greater cushioning or rebound effects actually increase the burden around the ankles and joints (Malisoux et al., 2022), which can in turn, result in higher prevalence of impact-related injuries such as shin splints (Bhusari & Deshmukh, 2023). The results of Round 2 possess further practical implications. Round 2 results showed that holding spring stiffness constant while varying body mass led to distinct motion trajectories, suggesting that people with different body

weights elicit highly differentiated running stability. This implicates that a more precise and individually tailored shoe softness system is needed for people with different body weights.

This study also provides an exemplar for integrating numerical methodologies and locomotion studies through computational pathways such as Matlab simulation. By implementing a computational simulator model, this study processed a detailed framework of human locomotion that consisted of various parameters, and visualized this framework through contemporarily generated graphs of motion trajectories. It is evident that via such computational pathways, analyses of gait stability have become more intuitive and controllable, as in, for example, how clearly the utilized model can inform human locomotion and gaits merely via altered parameter values. This study consolidates the future prospects of further studying human locomotion or other physical mechanisms through computational simulation.

6. Conclusion

The current study successfully utilized a computationally simulated model to represent the Spring Mass Model and to investigate the potential relationship between shoe softness and body weight in terms of how they interact to influence the gait of running. To conclude, the results of simulations show that overly soft shoes fail to provide adequate rebound and can cause the running gait to collapse, and overly stiff shoes provide excessive rebound that destabilizes the running gait. The results implicate increased prevalence of fatigue or overuse muscle injury when shoes are overly soft, and impact-related injury due to excessive loads to ankles and joints when shoes are overly stiff. These findings enlighten the importance for footwear industry to establish a more flexible system in which factors that determine shoe softness, such as materials of the cushioning, need to be considered carefully in accordance with each user's body weight. Despite having demonstrated how computational methodologies can be used to understand human locomotion, this study is limited by the simplicity of the Spring Mass Model due to its assumed exclusion of factors such as neuromuscular control and air resistance. Future research is urged to further the integration between more advanced computational and numerical methodologies and more complex locomotion frameworks, in order to promote the simulation models' accuracy and how they can be used to reflect on other practical locomotion-related issues.

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