Journal of Biomechanics 49 (2016) 691–697

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Effects of independently altering body weight and mass on the energetic cost of a human running model

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ARTICLE INFO

Article history:
Accepted 28 January 2016

Keywords:
Running
Energetics
Metabolic cost
Mechanical work
Leg stiffness
Locomotion

ABSTRACT

The mechanisms underlying the metabolic cost of running, and legged locomotion in general, remain to be well understood. Prior experimental studies show that the metabolic cost of human running correlates well with the vertical force generated to support body weight, the mechanical work done, and changes in the effective leg stiffness. Further, previous work shows that the metabolic cost of running decreases with decreasing body weight, increases with increasing body weight and mass, and does not significantly change with changing body mass alone. In the present study, we seek to uncover the basic mechanism underlying this existing experimental data. We find that an actuated spring-mass mechanism representing the effective mechanics of human running provides a mechanistic explanation for the previously reported changes in the metabolic cost of human running if the dimensionless relative leg stiffness (effective stiffness normalized by body weight and leg length) is regulated to be constant. The model presented in this paper provides a mechanical explanation for the changes in metabolic cost due to changing body weight and mass which have been previously measured experimentally and highlights the importance of active leg stiffness regulation during human running.

1. Introduction

Running over level ground requires a significant amount of energy despite the energy storage and return of spring-like legs (Cavagna et al., 1977). There are many components of human running that impart a metabolic cost, including supporting the weight of the body (Farley and McMahon, 1992; Kram and Taylor, 1990; Taylor et al., 1980; Teunissen et al., 2007), braking and propelling the body center of mass in the horizontal direction (Chang and Kram, 1999), swinging the legs about the hip (Gottschall and Kram, 2003; Modica and Kram, 2005; Moed and Kram, 2005), and swinging the arms (Arellano and Kram, 2011; Pontzer et al., 2009).

Prior studies show that generating force to support body weight, or the gravitational force acting on the body, is the primary determinant of the metabolic cost of running (Farley and McMahon, 1992; Kram and Taylor, 1990; Taylor et al., 1980; Teunissen et al., 2007). To better understand the metabolic cost required to support the weight of the body, prior experiments manipulated the effective body weight and mass of runners using weights attached to the waist and a reduced gravity apparatus over an instrumented treadmill (see Fig. 1 for an illustration of previous experiments and Supplemental material for further discussion). These experiments showed that the net metabolic rate of running decreased linearly as body weight was reduced (Farley and McMahon, 1992; Teunissen et al., 2007), increased in direct or slightly more than direct proportion to added body weight and mass (Epstein et al., 1987; Taylor et al., 1980; Teunissen et al., 2007), and was not significantly different from normal running with added mass alone (Teunissen et al., 2007).

The mechanisms that can explain these trends in the metabolic cost of running with changing mass and gravity are not well understood. Prior work shows that the metabolic cost of running is directly proportional to the whole-body mechanical work done by the body over a range of relatively slow running speeds near 3 m/s (Arampatzis et al., 2000; Bijker et al., 2001; Cavagna et al., 1977; Farris and Sawicki, 2012; Ito et al., 1983; Kaneko, 1990; Lacour and Bourdin, 2015). Though the precise relationship between the mechanical work performed by muscle-tendon units in the leg and the metabolic cost of running is complex (Albracht and Arampatzis, 2013; Arampatzis et al., 2006; Farris and Sawicki, 2012; Fletcher et al., 2013, 2010; Lacour and Bourdin, 2015), examining the total mechanical work done at the whole-body level may provide insight into the changes in the metabolic cost of running with changes in mass and gravity.

Further, a recent study showed that the effective stiffness of the leg increases during human running almost in direct proportion to increased body weight (Silder et al., 2015). This almost proportional increase in leg stiffness coincides with a similar increase in the metabolic cost of running with added body weight, indicating that changes in leg stiffness appear to correlate with changes in

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http://dx.doi.org/10.1016/j.jbiomech.2016.01.016
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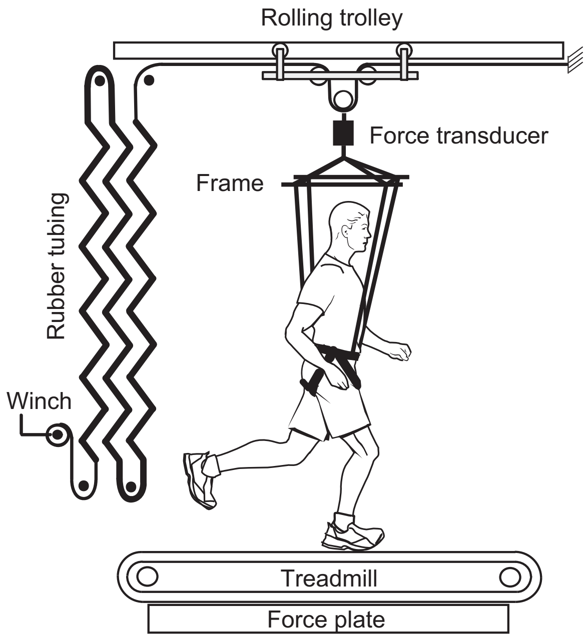

Fig. 1. Reduced gravity apparatus (reproduced/adapted with permission from Teunissen et al. (2007)).

the metabolic cost of running and body weight. Further, since the effective leg stiffness is often approximated by dividing vertical ground reaction force by the effective leg deflection (Silder et al., 2015), we expect that there is a connection between leg stiffness and generating vertical force to support body weight, which is the primary determinant of the metabolic cost of running. Recent modeling work suggests that a strong connection between the chosen leg stiffness and the mechanical cost of transport may exist for humans and animals (Shen and Seipel, 2015a).

We hypothesize that the changes in the metabolic cost of human running with varying body weight and mass (Teunissen et al., 2007) can be largely explained by the changes in the positive mechanical work done (Farris and Sawicki, 2012) during running if a dimensionless relative leg stiffness is maintained (Blickhan and Full, 1993; Shen and Seipel, 2015a). To this end, we developed a relatively simple open-loop mathematical model of human running to calculate the positive mechanical work done during running when body weight and mass were independently varied and leg stiffness was fixed or changed in proportion to body weight and mass. Our results show that changes in the positive mechanical work done by the leg in the simulation closely correlate with the changes in the metabolic cost of human running measured experimentally when the dimensionless relative leg stiffness is maintained. The model provides a mechanistic explanation for the energetic trends of human running and highlights the importance of active leg stiffness regulation during human running.

2. Methods

2.1. Actuated SLIP model of human running

Prior work shows that the whole body center of mass motion during human running can be approximated by a mass bouncing in the sagittal plane on a spring-like leg, like a pogo stick, as represented by the spring-loaded-inverted-pendulum (SLIP) model (Blickhan and Full, 1993; Blickhan, 1989). Since the canonical SLIP model is energy conserving, we required a model which has a mechanism for energy input and removal to study the effects of body weight and mass on the energetic cost of running.

In the present study, we used a variant of the recently developed Hip-Actuated SLIP model of legged locomotion (Shen and Seipel, 2012): See Fig. 2. This model has been shown to be highly-stable across a wide range of parameters and can predict realistic center-of-mass dynamics of human running using approximate human parameters. Unlike the traditional energy-conserving SLIP model, the open-loop Hip-Actuated SLIP model inputs energy into the system by torqueing the effective spring-leg about the hip and removes energy from the system through a damper acting along the leg. The parameters used in this model were selected to approximate the average human subject in a prior experiment (Teunissen et al., 2007) for comparison and are summarized in Table 1.

Table 1
The parameters used to approximate human running in this study were based on prior experimental work and chosen such that the model was stable over the parameter range with fore-aft dynamics that resemble human running. Many of the effective human parameters may change in practice while running based on subject variability, such as the leg stiffness, damping, human body mass, landing angle, and leg torque. We estimated and fixed the model parameters based on the available data for an average human runner.

Parameter	Name	Value
k	Leg stiffness	$k = mg^* K_{rel}/L_0$ N/m (Blickhan and Full, 1993)
K_{rel}	Dimensionless relative leg stiffness	20–25 (Farley and Gonzalez, 1996; Shen and Seipel, 2015a)
c	Effective “bilinear” leg damping	20,000 Ns/m^2 (Abraham et al., 2015)
m	Human body mass	63.3 kg (Teunissen et al., 2007)
l_0	Effective leg length from the human center of mass to the distal leg position (Foot)	1 m (Geyer et al., 2006; Shen and Seipel, 2012)
β	Leg landing angle beta	65° (Shen and Seipel, 2012)
τ	Leg torque	Variable (Table 2)
v_t	Target running speed	3 m/s (Teunissen et al., 2007)
g	Gravity	9.81 m/s^2

The equations of motion of the Hip-Actuated SLIP model can be derived via Newton's method (Shen and Seipel, 2012). The angle θ of the leg during the stance phase with respect to the horizontal axis is

$$\theta = \frac{\pi}{2} - \tan^{-1}\left(\frac{x - x_f}{y}\right) \quad (1)$$

The “foot” position x_f is the distal point of the effective spring-leg in contact with the ground at leg touchdown during the stance phase, or the approximate foot center of pressure. The position of the body center of mass is described by the coordinates x and y.

The leg length of the effective spring-leg and its derivative during the stance phase are

$$l = \sqrt{\left((x - x_f)^2 + y^2\right)} \quad (2)$$

$$\dot{l} = \frac{(x - f)\dot{x} + y\dot{y}}{l} \quad (3)$$

The forcing along the legs can be described by the force in the effective leg-spring and the effective damping force,

$$F_L = k(l_o - l) - c\dot{l}(l_0 - l) \quad (4)$$

It is important to note that in the present model we used a “bilinear” damping term $(l_0 - l)$ (Abraham et al., 2015) instead of a more typical linear damping term as was used in prior work (Potwar et al., 2014; Shen and Seipel, 2015a, 2015b, 2012). The bilinear damping model was chosen because it enables the Hip-Actuated SLIP model to approximate human ground reaction forces more accurately than the linear damping model (Abraham et al., 2015). The lowest leg damping parameter which ensured stability for all simulations was $c = 14{,}000$ Ns/m^2, but we chose $c = 20{,}000$ Ns/m^2 in this paper based on the value used in prior work which showed a good agreement between the simulated vertical ground reaction forces and experimental data (Abraham et al., 2015). We also show results for varying leg damping and a linear damping model in the supplemental material section.

Initially, we assumed that the leg stiffness k was a constant value despite changing mass and gravity conditions. However, a recent study showed that the effective stiffness of the leg increases almost in direct proportion to added body mass during human running (Silder et al., 2015). Therefore, we hypothesized that the leg stiffness k may vary to maintain a constant dimensionless relative leg stiffness, K_{rel}. Prior work has shown that humans and animals tend to adapt their leg stiffness to maintain an approximately constant dimensionless effective stiffness, which varies between 10 and 20 for animal