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Effects of human running cadence and experimental validation of the bouncing ball model

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ABSTRACT

The biomechanical analysis of human running is a complex problem, because of the large number of parameters and degrees of freedom. However, simplified models can be constructed, which are usually characterized by some fundamental parameters, like step length, foot strike pattern and cadence. The bouncing ball model of human running is analysed theoretically and experimentally in this work. It is a minimally complex dynamic model when the aim is to estimate the energy cost of running and the tendency of ground-foot impact intensity as a function of cadence. The model shows that cadence has a direct effect on energy efficiency of running and ground-foot impact intensity. Furthermore, it shows that higher cadence implies lower risk of injury and better energy efficiency. An experimental data collection of 121 amateur runners is presented. The experimental results validate the model and provides information about the walk-to-run transition speed and the typical development of cadence and grounded phase ratio in different running speed ranges.

1. Introduction

Professional runners' training process involves the biomechanical analysis of their body motion. In contrast, amateur runners usually do not focus on the development of injury preventing and energy efficient running form. However, considerable improvement can be achieved by taking into consideration some basic biomechanical rules. A lot of materials from the Internet and magazines discuss the improvement of running style. However, these information are contradictory in many issues and they are mostly based on personal experience and not on thorough scientific investigation. Present work aims to contribute to the actual researches related to the understanding of the biomechanics of human running.

Many works like [1,2] contribute to the thorough understanding of bipedal locomotion, human walking and running. Several approaches and organizations [3–5] have been developed which aim to gather and disseminate practical, science based knowledge about healthy, injury preventing, energy efficient and natural way of running. Researchers apply different types of biomechanical models of a wide range of complexity. A lot of complex high degree of freedom (DoF) mechanical models exist, which are suitable for motion capturing, dynamic and kinematic analysis of the human body and running motion carefully. However these investigations are hard to use for prediction regarding the effect of a parameter modification, due to the extremely large number of variables. However, in the case, when a specific issue is investigated, simplified dynamical models may be more predictive than a very complex, high DoF model with large number of parameters.

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Starting from the most complex models, e.g. [6] towards the simplest ones, we can mention some low DoF segmental models [7–10] and some spring legged models [11,12], besides many other examples.

The most fundamental parameters, with which the running form can be characterized, are running speed, step length, *step frequency* and strike pattern besides many other parameters. Many articles study the effect of step frequency also known as *cadence*, which indicates the average number of steps within one-minute-long time duration. The effect of cadence c is in the focus of this work, which is considered to be one of the most important parameters, when running form is analysed [13–17]. The bouncing ball model was introduced in [18], which is the simplest possible model for the investigation of the dynamic effects of cadence. Present work details an extended theoretical and experimental study of the bouncing ball model.

One can choose from infinite number of alternatives of step length s and cadence c value pairs at a certain running speed $v_x = s\,c$. It is demonstrated by the experiments explained in [13] that the optimal cadence, when the oxygen uptake (the indicator of physical loading of the body) is minimal, and the freely chosen convenient cadence are not the same for most of the people. Present work aims to find practical directives that help the choice of proper cadence value.

Present paper aims to show that cadence has a direct effect on energy efficiency and ground-foot impact intensity by means of a simple dynamic model. The simple but still useful estimations are based on the dynamics of a bouncing ball.

The bouncing ball model of running is validated by measurements in [18] involving the measurement data of 41 people. Present work provides an extended experiment with 121 people and thorough mechanical and statistical analysis of the collected data. The effect of the ratio of the flight phase and the grounded phase is considered in this work, in contrast to [18], where zero grounded phase was assumed. In the present work we determined the flight phase value for which the bouncing ball model and the reality are the closest to each other. The results of [18] are extended by the model based estimation of the mechanical power which is absorbed by ground-foot collision. Besides, present analysis of the measured data confirmed the typical speed of walk-to-run transition that can be found in the literature.

2. Theoretical background

The bouncing ball model and its application for predicting energy efficiency and ground-foot impact intensity are detailed in this section.

2.1. The bouncing ball model

The mass of the body is shrunken into a single point mass m located in the centre of gravity (CoG) during flight phase. The model considers gravity and impulsive ground reaction force, while other external forces, like aerodynamic forces, are neglected. The parabolic path of the CoG during flight phase is in the vertical (x–y) plane depicted in Fig. 1 (left). We assume that the parabolic path is identical in each step, for which the necessary amount of energy is provided by the runner. The complete time period T of each step is separated into grounded phase T_g and flight phase T_f as the t–y plot in Fig. 1 (right) shows. Each parabolic segment with time duration T_f starts from the same location where the previous one ends, but time T_g passes between.

The bouncing ball is a minimally complex model, which is suitable only for the investigation of the effects of cadence on the ground-foot impact intensity and the collision induced energy absorption. The model is limited to find approximate relation between cadence, vertical displacement amplitude of the CoG of the body and mechanical power consumption of running. Many kinematic and dynamic parameters are ignored, such as posture of the body during the gait cycle, strike pattern or flexibility of muscles, tendons and footwear.

The motion of the CoG during flight phase is described by the following kinematic equations:

$$x(t) = x_0 + \dot{x}_0 t, \tag{1}$$

$$y(t) = y_0 + \dot{y}_0 t - \frac{g}{2}t^2, \tag{2}$$

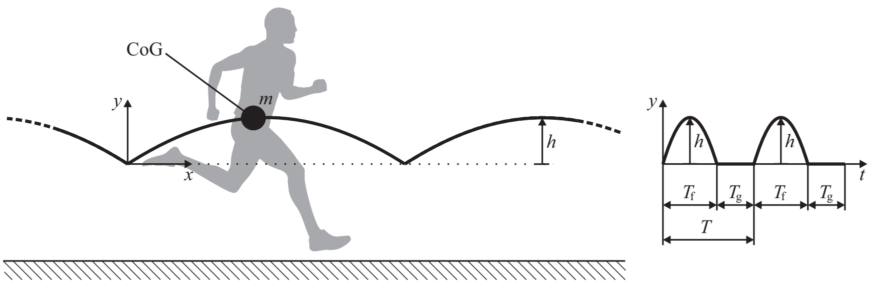

Fig. 1. Idealized path of a runner's CoG (left) and time history of the CoG vertical position (right).