Journal of Biomechanics 46 (2013) 2207–2212

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Linear center-of-mass dynamics emerge from non-linear leg-spring properties in human hopping

Sebastian Riese*, Andre Seyfarth, Sten Grimmer

Lauflabor Locomotion Laboratory, Institute for Sport Science, Technische Universität Darmstadt, Magdalenenstraße 27, D-64289 Darmstadt, Germany

ARTICLE INFO

Article history:
Accepted 28 June 2013

Keywords:
Biomechanics
Hopping
Spring–mass model

ABSTRACT

Given the almost linear relationship between ground-reaction force and leg length, bouncy gaits are commonly described using spring–mass models with constant leg-spring parameters. In biological systems, however, spring-like properties of limbs may change over time. Therefore, it was investigated how much variation of leg-spring parameters is present during vertical human hopping. In order to do so, rest-length and stiffness profiles were estimated from ground-reaction forces and center-of-mass dynamics measured in human hopping. Trials included five hopping frequencies ranging from 1.2 to 3.6 Hz. Results show that, even though stiffness and rest length vary during stance, for most frequencies the center-of-mass dynamics still resemble those of a linear spring–mass hopper. Rest-length and stiffness profiles differ for slow and fast hopping. Furthermore, at 1.2 Hz two distinct control schemes were observed.

1. Introduction

For bouncy gaits the center-of-mass (CoM) movement can be approximated by a ballistic trajectory during flight and a spring law counteracting gravity during stance. This finding resulted in the theoretical concept of the spring-loaded inverted pendulum (SLIP) model for hopping and running (Blickhan, 1989; McMahon and Cheng, 1990). Here, the body is represented by a point mass and the leg is described by a massless linear spring. This approach is supported by the force–length function (FLF) of the leg, describing the relationship between ground-reaction force (GRF) and instantaneous leg length (Farley et al., 1991; Blickhan and Full, 1993).

So far, it is unclear where global spring-like behavior of the leg originates. Some studies suggest that non-linear visco-elastic properties of the muscle–tendon complex, so-called “preflexes”, are the main contributors, especially during fast movements (Loeb Brown and Loeb, 1997). Others argue that muscle activation determines global leg behavior (Bobbert and Richard Casius, 2011). Also, combined control schemes incorporating preflexes and feed-forward patterns have been suggested (Cham et al., 2000).

If leg segmentation is taken into account, linearity of leg behavior is lost on joint level. Even though the moment–angle relationship of the ankle joint is fairly linear for a variety of running patterns, this is not the case for the knee joint (Guenther and Blickhan, 2002). Results of Rapoport et al. (2003) support the loss of linearity on joint level. Using a segmented sagittal-plane hopping model for data analysis, joint stiffness was found to increase with joint flexion, resulting in bell-shaped stiffness profiles over time with maximum stiffness near midstance.

Leg compliance and its adaptation in response to changing environmental conditions are hypothesized to be crucial for successful locomotion (Grimmer et al., 2008). In contrast to serial-elastic actuators (SEAs), tunable compliant actuators allow to change mechanical stiffness on-the-fly. Hence, it was argued by Hurst et al. (2004) that this concept “could result in an effective actuation method for highly dynamic legged locomotion”.

Following this argument, it was shown for a one-dimensional spring–mass model that simultaneous variations of leg-spring parameters (stiffness, rest length) during ground contact result in stable, robust and efficient hopping (Riese and Seyfarth, 2012a,b), motivating the variable-leg-spring (VLS) concept. So far, the results of previous studies indicate variations of leg stiffness and rest length during human hopping (Farley et al., 1991; Hobara et al., 2011), however without explicitly addressing them.

Thus, in order to validate the VLS concept with experimental data, here the behavior of leg stiffness and rest length in vertical human hopping is investigated, assuming a tunable leg spring (Fig. 1). We hypothesize that the linear CoM dynamics observed in human hopping result from the interaction of non-linear leg-spring properties, namely non-constant leg stiffness and rest length, and that these parameter variations may be of considerable magnitude ($>10\%$ of the touchdown value).

According to Farley et al. (1991) human hopping patterns for frequencies below the preferred frequency differ from those above

* Corresponding author. Tel.: +49 6151 163163.
E-mail address: sebastian.riese@uni-jena.de (S. Riese).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.06.019

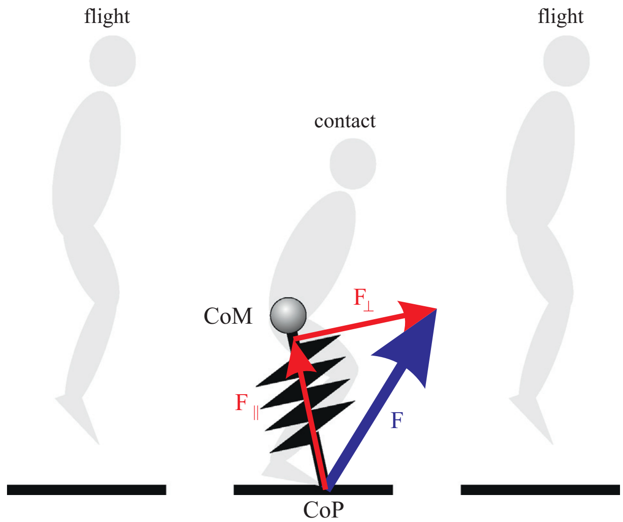

Fig. 1. SLIP model during human hopping. All mass is located in the center of mass (CoM) and the leg length is assumed to be the distance between CoM and center of pressure (CoP). The misalignment of ground-reaction force (GRF) and leg spring was exaggerated to illustrate the GRF contributions parallel and perpendicular to the leg direction, $F_\parallel$ and $F_\perp$, respectively.

the preferred one. Furthermore, it was shown that humans employ different control strategies to stabilize hopping depending on the rate of movement (Yen and Chang, 2010; Hobara et al., 2011). As the parameters accessible for control in the one-dimensional spring–mass model are stiffness and rest length, we expect slow hopping to exhibit different stiffness and rest-length profiles than fast hopping.

2. Methods

2.1. Experimental setup

Six healthy, well-trained male subjects (76.5 ± 8.4 kg) participated in the study. Prior to the measurements, the experiment was approved by the ethics review board of the University of Jena, as laid out in the Declaration of Helsinki, and all subjects gave their written informed consent.

The subjects were asked to perform vertical jumps on both legs. Each subject was instructed to jump with self-selected frequency, subsequently referred to as f_p (Table 1). Additionally, following Farley et al. (1991), the hopping frequencies 1.2 Hz, 1.8 Hz, 2.8 Hz and 3.6 Hz were prescribed with a metronome. The sequence of hopping frequencies was randomized for each subject.

Each trial was of 30 s length. At the beginning and end of each trial, the subjects were asked to stand quiet for 5 s, leaving 20 s of vertical hopping, resulting in approximately 20–50 hopping cycles depending on subject and frequency.

2.2. Kinetics and kinematics

GRFs were measured directly with 1 kHz using a Kistler force platform. Additionally, center-of-pressure (CoP) position was extracted from this data.

In order to obtain kinematics, 17 reflective markers were placed on anatomical landmarks of each subject (Table 2). Marker positions were measured with 240 Hz using a ten-camera infrared system (Proflex MCU240, Qualisys, Gothenburg, Sweden) and interpolated to 1 kHz to match the GRF and CoP data. CoM position was then calculated in accordance with Dempster's body-segment parameter data (Dempster, 1955; Winter, 2009).

2.3. Estimation of stiffness and rest length

In order to estimate global leg properties, the leg was approximated as a massless spring, connecting CoM and CoP (Fig. 1). GRFs and CoM movement during stance were projected into leg direction. Therefore, the data set is reduced to one-dimensional (vertical) hopping.

Additionally, GRFs were normalized to body weight (BW) and instantaneous leg length was normalized to initial CoM height l_{init}, i.e. leg length while standing quiet. Thus, estimated stiffness $K = kl_{\text{init}}/\text{BW}$ and rest length $L_0 = l_0/l_{\text{init}}$ are non-dimensional. As the GRF and leg-length data are noisy, both data sets were filtered using a lowpass Butterworth of 5th order, with a cut-off frequency of 25 Hz.

Table 1
Preferred frequency f_p. The overall mean is in good agreement with results of Farley et al. (1991) (2.2 Hz).

Subject	**mean ± s.d. (Hz)**
1	2.01 ± 0.07
2	2.50 ± 0.13
3	2.42 ± 0.06
4	1.98 ± 0.04
5	2.76 ± 0.14
6	2.22 ± 0.05
Overall	2.33 ± 0.30

Table 2
Marker set for calculation of kinematics.

Marker placement
Forehead
Right temple
Left temple
Light acromion
Left acromion
Right trochanter
Left trochanter
Right lateral elbow
Left lateral elbow
Right lateral wrist
Left lateral wrist
Right lateral knee
Left lateral knee
Right lateral malleolus
Left lateral malleolus
Right 5 metatarsals
Left 5 metatarsals

For each trial, stance phases ($F_\parallel \geq 0.01$ BW) were extracted and normalized to 100% stance time. $F_\parallel$ and leg length L were interpolated accordingly. Following previous studies (Rozendaal and van Soest, 2008; Peter et al., 2009) and assuming a piecewise-linear spring with stiffness $K(i)$ and rest length $L_0(i)$, the equation

$$\begin{pmatrix} F_\parallel(i) \\ F_\parallel(i+1) \end{pmatrix} = K(i) \cdot \begin{pmatrix} L_0(i) - L(i) \\ L_0(i) - L(i+1) \end{pmatrix} \quad (1)$$

had to be solved for the time steps $i = 1, 3, \ldots, 99$. As there are two unknowns per time step, $K(i)$ and $L_0(i)$, it was assumed that $K(i) \equiv K(i+1)$ and $L_0(i) \equiv L_0(i+1)$. Within this approach the spring is approximated as linear with constant parameters for two consecutive time steps. However, the resulting parameter profiles may be non-constant, allowing for a non-linear spring throughout stance. To ensure physically meaningful solutions, stiffness is constrained to values $K(i) > 0$. Accordingly, during stance rest length has to satisfy $L_0(i) > L(i)$, as $L_0 = L$ denotes the transition from flight to stance phases and vice versa.

As a first approach, stiffness and rest length were calculated directly by solving Eq. (1) analytically for $K(i)$ and $L_0(i)$. However, the constraints for stiffness and rest length were violated for a considerable amount of time steps, especially for frequencies below the preferred frequency f_p. Thus, Eq. (1) was solved numerically with the least-squares method *lsqcurvefit* implemented in MATLAB (R2010a, The MathWorks Inc., Natick, MA, USA) using the constraints for $K(i)$ and $L_0(i)$ as lower boundaries.

3. Results

Except at 1.2 Hz, results presented here for a given frequency are means over all trials of all six subjects at that frequency. At 1.2 Hz, behavior of half of the subjects distinctively differs from that of the other half, thus denoted in the figures as “1.2 Hz I” and “1.2 Hz II”, respectively.

3.1. Measured data

For frequencies from f_p to 3.6 Hz, instantaneous leg length $L(i)$ corresponds to running-like single-minimum CoM trajectories (Fig. 2a). At lower frequencies, 1.2 and 1.8 Hz, also double-minimum