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The natural shock absorption of the leg spring

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ABSTRACT

When a human being runs, muscles, tendons, and ligaments together behave like a single linear spring. This "leg spring" can be described remarkably well by spring/mass models. Although leg-stiffness during running (and logically, therefore, in hopping) has been shown to be adjusted in line with the individual characteristics of the external contact surface, the relative contribution of each of the sub-components of the leg spring to the mechanics of running is unclear.

We proposed the three-degree-of-freedom leg spring chain in a position of stable equilibrium under the action of the leg stiffness. If the leg spring receives a displacement in hopping, the forces will no longer equilibrate, but the system will be exposed to the action of a force on a leg spring chain. We thus have two corresponding sets of modes, one set being the mode about which the chain is displaced, the other set for the forces which are evoked in consequence of the displacement. We found that if the leg has been displaced from a position of equilibrium about one of harmonic modes, then a vibration about this harmonic mode evokes a system of forces in the leg spring which in its turn tends to produce a motion on the original harmonic mode, and thus produce oscillation about the same harmonic mode. Our results suggest that the desired harmonic mode can be explained in terms of the natural shock absorption ability of the leg.

1. Introduction

When a human runs or hops the centre of mass of his/her body rises and falls in a manner that is similar to that of a bouncing ball (McMahon and Cheng, 1990). The latter analogy was also used by Ferris and Farley (1997) when they asked whether one modifies the spring-like properties of our legs to suit the elastic properties of the floor or ground on/across when running. Human movement control can be seen as a process that is distributed over the performer–environment system rather than being localized in an internal structure of the performer (Gibson, 1979). In a recent study (Kim et al., 2011) confirmed that leg stiffness is not directly related to running mechanics, but rather, to the running environment. The performer and his/her environment (surface) may be said to be co-participant in any resulting action. In this way, actions are specific to function rather than to mechanism (Reed, 1985). Movements and postures are controlled and coordinated to realize functionally specific acts that are themselves based on the perception of affordances i.e., possibilities for actions (Gibson, 1979). Therefore, during the hopping, we first investigated about the complementarities between the perception of the surface and the co-perception of the self in terms of special posture (i.e., natural modes) because the two are inseparable.

The mechanical properties of the mass–spring–damper (MSD) elements are not constant but are adjustable to environmental parameters (Nikooyan and Zadpoor, 2011). The various types of single degree of freedom (SDOF) or multi degree of freedom (MDOF) MSD models have been reviewed (Nikooyan and Zadpoor, 2011). They have emphasized how models use to take account the foot–ground interaction as environmental parameters (Kim et al., 1994; Liu and Nigg, 2000). An optimal controller has been added to the model such that the changes in ground reaction force (GRF) are minimal (Zadpoor and Nikooyan, 2010).

The dynamics of a leg spring which has freedom of the third order, included as a hopping model in this investigation consists of three interconnected masses with three springs. If natural frequencies and modes in three natural vibration are available during an activity, then it is easy to visualize the motion of the system in each mode (Hatch, 2001), which is the first step in being able to understand how lower extremity stiffness could impact on running performance and or injury risk.

Since this work addresses the problem of estimating leg stiffness using motion data acquired from a physical hopping test, the estimation methods used in model are closely related to systems parameter identification and estimation which are

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regularly used in other areas of science and engineering (Friswell and Mottershead, 1995). This paper attempts to introduce a modelling technique, using inverse problems (Kim et al., 2009) to identify individual variations in terms of parameters within biomechanical models.

In order to solve inverse problems for identification of systems with known degree of freedom, the technique of Bellman-Quasilinearization (Kalaba and Spingarn, 1982; Kim and Voloshin, 1995; Kim et al., 1994) was implemented. This technique allows for the treatment of both observational data and design data in the same manner. The problem we wish to consider is how to determine both stiffness and damping in the leg spring from observations of the vertical displacements of the individual limb segments for a stance phase of hopping.

A secondary aim of our study addressed the mechanism of stiffness adjustment within the leg spring to attune the foot–surface perception, permitting the vibration suppression function. We have hypothesized that rather than being localized either in an internal structure of the performer or in his or her environment (for example, the foot–surface interaction), control of the shock absorption is distributed over the performer–surface system (Gibson, 1979). The implication of these findings in conjunction with the functioning of the ‘natural shock absorber’ will be discussed in the later section of this paper.

2. Methodology

2.1. Identification of the leg spring parameters via Bellman-Quasilinearization

Bobbert et al. (1992) have stated that it is reasonable to assume that injuries are related to phenomena that occur during the stance phase of a stride. To

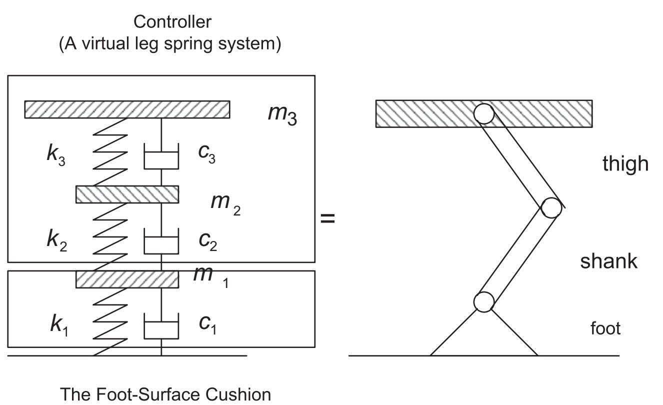

Fig. 1. The three-degree-of-freedom leg spring model explains how the system can perform the vibration suppression function. The model consists of a SDOF of foot–ground contact and MDOF (two degrees) of dynamic controller that is directly attached to the former. This feature stands in contrast to the muscle control optimization such as computed muscle control (Delp et al., 2007) in which the control gains do not necessarily have any physiological meanings. The second-order controller will generate the control inputs as if it comes from an attached MSD system to the foot–surface.

Table 1
Anatomical counterparts of the parameters that are illustrated in Fig. 1.

Anatomical analogy	Leg parameters
Mass of foot (e.g., 0.928 kg)	m_1
Mass of shank (e.g., 2.976 kg)	m_2
Mass of rest of body (e.g., 51.648 kg)	m_3
Integrated musculoskeletal system with foot–floor contact including ankle flexor tendon, plantar fascia and the ligaments of the arch (N/m for k and Ns/m for c)	$k_1(c_1)$
Integrated musculoskeletal system such as bony contacts, ligaments and cartilage, and involving muscle actions surrounding the ankle joint	$k_2(c_2)$
Integrated musculoskeletal system such as bony contacts, ligaments and cartilage, and involving muscle actions surrounding the knee joint	$k_3(c_3)$
Position (velocity) of m_1	$x_1(\dot{x}_1)$
Position (velocity) of m_2	$x_2(\dot{x}_2)$
Position (velocity) of m_3	$x_3(\dot{x}_3)$

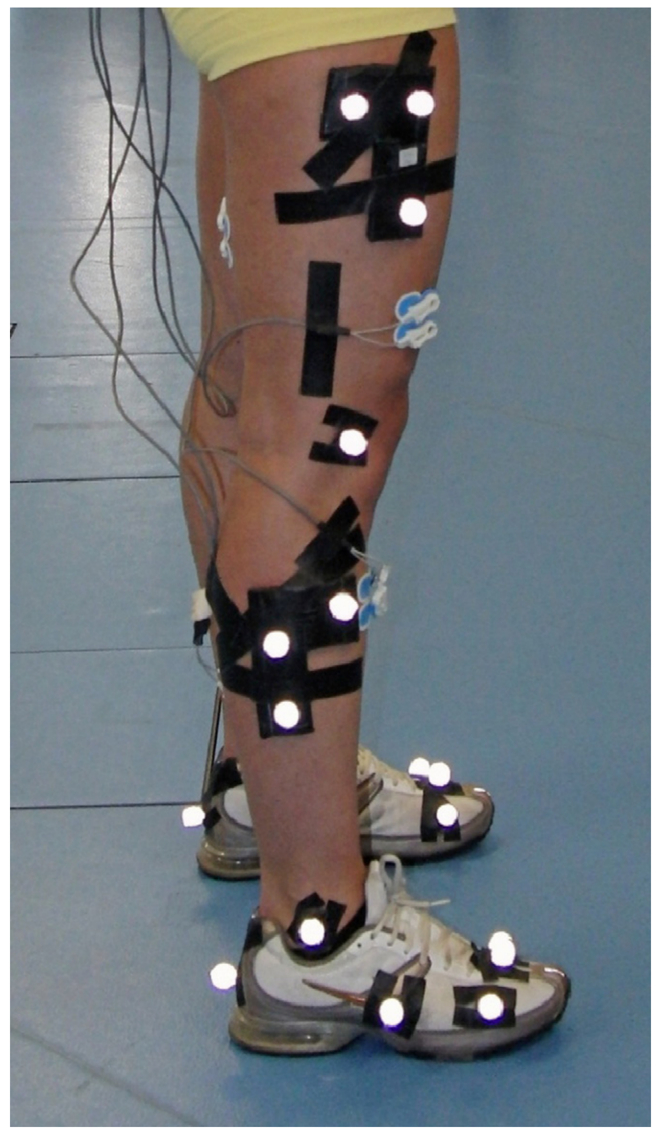

Fig. 2. Surface markers (indicated by bright dots) were used to predict the contribution of individual components of the leg spring to the stance phase of the hop. These markers were used for the reconstruction of six body segments (right and left thigh, right and left shanks and right and left feet). The current figure was taken at the stationary configuration. TA: electrodes placed at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus. GM: electrodes placed on the most prominent bulge of the muscle in the direction of the leg. SOL: electrodes placed at 2/3 of the line between the medial condylis of the femur to the medial malleolus. VL: electrodes placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella. BF: electrodes placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia, in the direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia. A ground electrode was placed over the C7 vertebrae.