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AN INVERSE METHOD FOR PREDICTING THE MECHANICS OF HOPPING FROM MOTION DATA INPUT

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By segmentation of the body, this study estimated both the natural frequency and mode shapes of the mechanics of hopping, during a stance phase, using a purposely developed three degree-of-freedom state space model of the leg. The model, which was validated via comparison of measured and estimated motion data, incorporated a novel use of the Bellman-Quasilinearization technique estimators. Vertical displacements of the centre of mass of each segment (thigh, shank, and foot) were collected during a stance phase and used as observed data for unknown leg compliance parameters. It was found that the relative joint contributions to compliance during an exhaustive hopping appear to be tuned in part, to the type of foot-surface landing (input signals).

KEY WORDS: leg compliance of an exhaustive hopping, tuning of the body segments, Bellman-Quasilinearization.

INTRODUCTION: When a human runs or hops the centre of mass of the body rises and falls like a bouncing ball. The analogy has proved helpful in several studies of running and hopping (McMahon & Cheng, 1990) and was used again by Ferris and Farley (Ferris & Farley, 1997). They ask whether we modify the spring like properties of our legs to suit the elastic properties of the floor or ground on which we are moving. They have found it convenient to study hopping in place rather than forward running. There are two ways of describing the properties of spring: the stiffness of spring and the compliance that is the reciprocal of stiffness. In this study, we use compliance, because the compliance of two springs connected in series is simply the sum of the compliances of the individual springs. Thus, when we hop or run on a springy floor, the compliance of the floors is added to the compliance of our legs. It was found that leg compliance was reduced as platform compliance increased, thus keeping the total compliance constant (Ferris, Liang, & Farley, 1999). In the recent study, this premise that leg compliance is not directly related to running mechanics, but rather, to the running environment was confirmed (Kim, Tan, Veloso, Vleck, & Voloshin, 2011). So far researchers have reported on the compliance of running/hopping in its environment (e.g., different surfaces) rather than on characterization of mechanics itself (e.g., relative joint contributions to compliance to the type of landing). If natural frequencies and mode shapes are available during an activity, then it is easy to visualize the motion of the system in each mode, which is the first step in being able to understand how lower extremity stiffness is implied for performance and injury. The detrimental effects of functional changes in impaired flexor tendons, such as exercised-induced muscle damage, on the leg compliance have yet to be adequately explored. Thus, the purposes of this study were to summarize the current knowledge of the spring-mass model and to propose a new paradigm for understanding of reaction of the locomotor system to repetitive impact forces, with special consideration of hopping. It was hypothesized that the presence of exercised-induced tendon fatigue would result in compliance mechanism in terms of the passive eccentric contraction of muscle tendon units (MTU) at the joints, thereby reflecting a disruption on the overall leg compliance.

METHODS: Eleven healthy subjects (4 women and 7 men) performed a sequence of unilateral hops on her/his dominant lower limb until exhaustions. To establish a control parameter for the hoping task, she/he performed a squat jump (SQJ) before and after the hoping task. The minimum height for the jumps during the fatigue task was 80% of the maximum height achieved in the first SQJ. Instantaneous visual feed back from a computer monitor regarding peak height and strong verbal encouragement from the examiner were provided to help maintain maximal efforts throughout the training session. The university ethics committee approved this study and the subject signed informed written consent. Motion capture was collected with an optoelectronic system of ten cameras (Qualisys, Oqus-300) operating at 200Hz and three vertical displacements at centre of mass of each segment (thigh, shank, and foot) were processed via Visual 3D. The electromyography signals of soleus was collected by using surface electrodes (Ambu Blue sensor N-00-S/25), according to the SENIAM project recommendation. The EMG data was transmitted by telemetry (Glonner Biotel 88), and sampled at 1 KHz. The three-degree-of-freedom model (Figure 1) was used to predict the vertical loading during hopping. The model consists of three masses, three springs and dashpots.

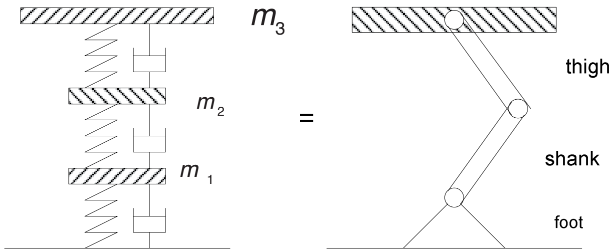

Figure 1: The three-degree-of-freedom leg compliance model was used to predict the contribution of individual component during stance.

The equations of motion are represented by the differential equations as

$$\begin{aligned} m_1\ddot{x}_1 &= -k_1x_1 - c_1\dot{x}_1 - k_2(x_1 - x_2) - c_2(\dot{x}_1 - \dot{x}_2) \\ m_2\ddot{x}_2 &= k_2(x_1 - x_2) + c_2(\dot{x}_1 - \dot{x}_2) - k_3(x_2 - x_3) - c_3(\dot{x}_2 - \dot{x}_3) \\ m_3\ddot{x}_3 &= k_3(x_2 - x_3) + c_3(\dot{x}_2 - \dot{x}_3) \end{aligned} \tag{1}$$

The parameters associated with leg compliance are presented with their anatomical analogies (Table 1).

Table 1
Anatomical analogy to parameters

Anatomical analogy	Leg parameters
mass of foot (e.g., 0.928kg)	m_1
mass of shank (e.g., 2.976kg)	m_2
mass of rest of body (e.g., 51.648kg)	m_3
ankle flexor tendon, plantar fascia and the ligaments of the arch (N/m for k and Ns/m for c)	$k_1\,(c_1)$
passive structures such as bony contacts, ligaments and cartilage, and by eccentric muscle actions surrounding the ankle joint	$k_2\,(c_2)$
passive structures such as bony contacts, ligaments and cartilage, and by eccentric muscle actions surrounding the knee joint	$k_3\,(c_3)$
positon (velocity) of m_1	$x_1(\dot{x}_1)$
positon (velocity) of m_2	$x_2(\dot{x}_2)$
positon (velocity) of m_3	$x_3(\dot{x}_3)$

We wish to determine the parameters (k_i and c_i) comprising the leg compliance from the observation of the linear displacements of m_i during a stance phase of time. Such a technique would reduce the necessity of foot-floor measurement. Those parameters would provide a unique insight into the physiological processes of hopping. Bellman-Quasilinearization(Bellman, Jacquez, Kalaba, & Schwimmer, 1976) plays a central role in this analysis and allows one to treat experimentally observed dada and design data in the same manner. The identification of parameters will refer to leg compliance system which is governed by differential equations (System equation 1) and whose behaviour is determined by a set of parameters which are unknown. Bellman sough to draw together quaisilinearization with the rich theory of dynamics programming to solve identification problem occurring mainly in the area of biomechanics(Bellman, 1967). We seek to determine the constant parameters k_i and c_i which are consistent with the observations made. That is, if k_i and c_i were used in a numerical solution of System equation (1), the results would best fit the observed displacements (velocities) (x_i ($\dot{x}_i$)) in a least squares sense(Roth, 1986). Having obtained the parameters, we solve the eigenvalue problem for identifying of the resonant frequencies and mode shapes, which are used to uncouple the original set of coupled equations, allowing a reduced number of vibrational response mode.

RESULTS: The comparison between the measured states and the simulated by the leg compliance model shows that the model adequately presents the observed states (Figure 2).

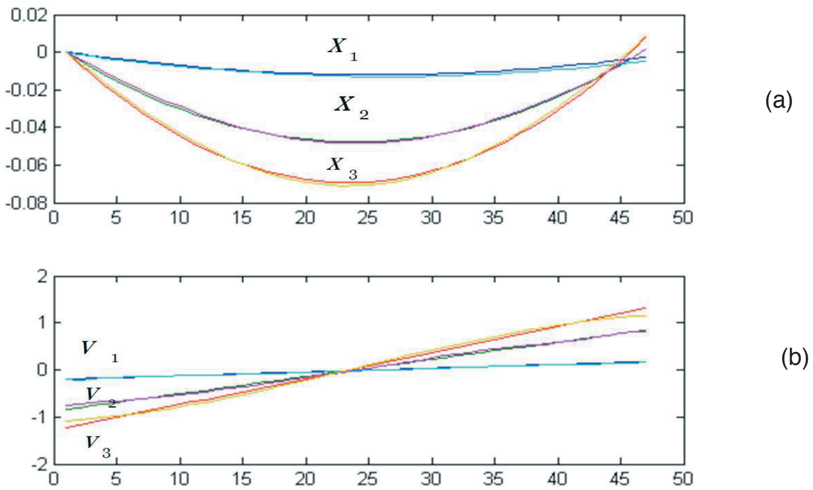

Figure 2: The comparison of the observed and model prediction of leg compliance of states (positions and velocities) (unit: m and m/sec) during stance: (a) Position (b) Velocities.

Having mode shapes means that at certain frequencies all points in the leg system will vibrate at the same frequency and in phase, i.e., all points during an acitivity will reach their maximum and minimum displacements at the same point in time (Figure 3-1, 3-2, and 3-3). The eigenvectors (mode shapes) are only known as ratios of displacements, not as absolute magnitudes. The resulting mode shapes and modes can be compared with known physiological processes to identify 'physically realistic' mode regimes, which happens to be the first mode (6.5 rad/sec) and high frequency modes that have little contribution to the system can be eliminated (here the second and third mode). It is the first mode that can reasonably represent the hopping activity and provide resonant frequencies and mode shapes.

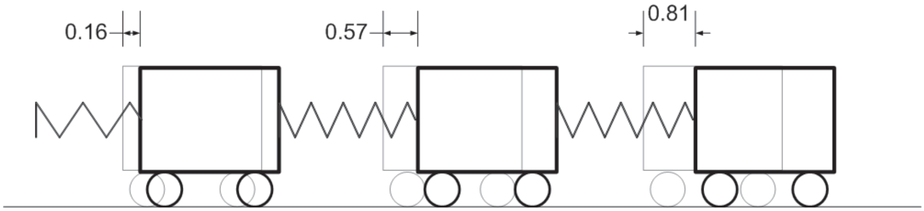

Figure 3-1. Mode shape plot for first mode (6.5 rad/sec), where all masses move in phase with less stress in the connecting springs (tissues).

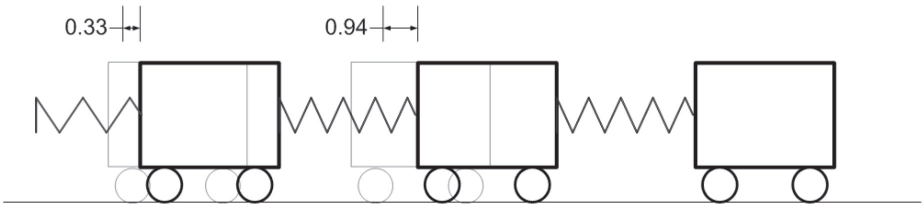

Figure 3-2. Mode shape plot for second mode (64.5 rad/sec), where third mass (The rest of body) stationary and the two masses move in phase with the first mass (foot), which is moving with one third of amplitude of the second mass (shank).

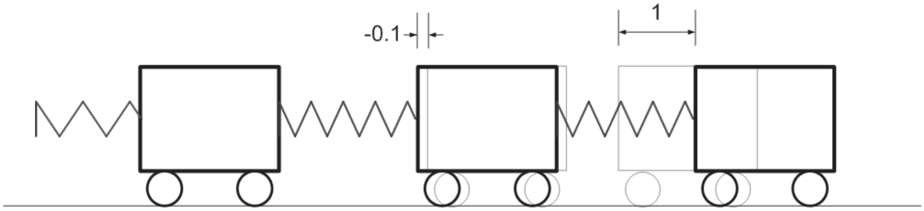

Figure 3-3. Mode shape plot for third mode (143.5 rad/sec), where first mass (The foot) stationary and the two masses move out of phase with the second mass (shank), which is moving with one tenths of amplitude of the third mass (the rest of body).

The five typical hops out of 40 hops that the subjects accomplished were analyzed in order to determine whether there were significant changes in the parameter contents with increases in the fatigue level. Although leg compliance was altered with hopping sequence, it could increase or decrease with fatigue level among subjects, resulting in that interaction is not significant (p=0.137) (Figure 4). However, the ratios of compliances at each segments would remain similar, showing lines are parallel (p=0.993; Figure 5). The tuning of the body segments to the input signals is done to minimize soft tissue vibration.

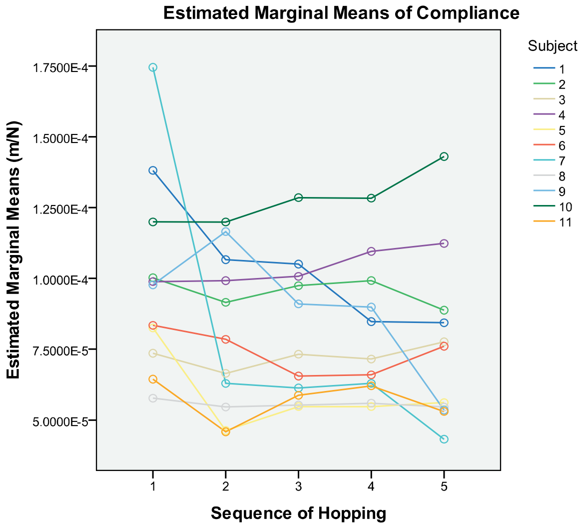

Figure 4: The alterations in leg compliance for eleven subjects (unit: m/N) as the fatigue level increases (1, 2...5).

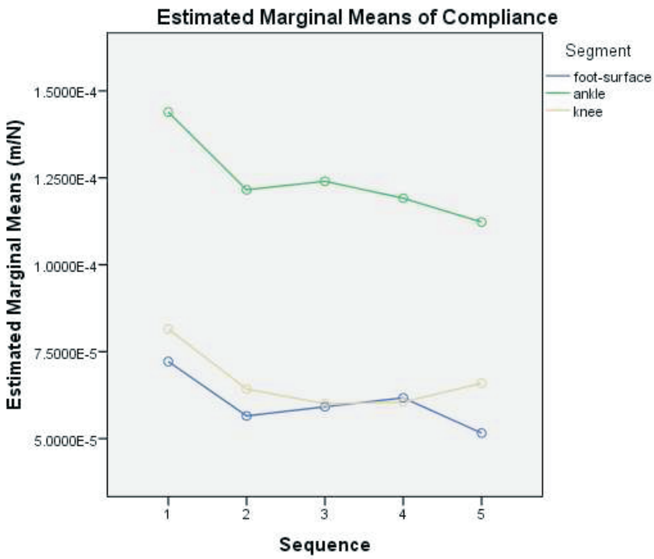

Figure 5. No significant interaction, i.e. contributions of compliances at each segments are tuned to the landing (in this case, foot-surface)—lines parallel.

DISCUSSION: The purpose of this investigation was to determine whether kinematics alteration a hopper makes when suffering from MTU damages and how these adjustments affect parameters within the leg compliance model. Impaired functional changes at flexor MTU resulting from excessive exercise-induced damages during hopping results in less significant interaction with leg compliance mechanism (p=0.137). Our findings demonstrate that human prefer to maintain the similar mechanics of hopping regardless of fatigue level, as visualized in terms of mode shapes (Figure 3-1). The relative joint contributions to compliance during an exhaustive hopping appear to be tuned in part, to the type of foot-surface landing (Figure 5).

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