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Leg stiffness measures depend on computational method

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ABSTRACT

Leg stiffness is often computed from ground reaction force (GRF) registrations of vertical hops to estimate the force-resisting capacity of the lower-extremity during ground contact, with leg stiffness values incorporated in a spring–mass model to describe human motion. Individual biomechanical characteristics, including leg stiffness, were investigated in 40 healthy males. Our aim is to report and discuss the use of 13 different computational methods for evaluating leg stiffness from a double-legged repetitive hopping task, using only GRF registrations. Four approximations for the velocity integration constant were combined with three mathematical expressions, giving 12 methods for computing stiffness using double integrations. One frequency-based method that considered ground contact times was also trialled. The 13 methods thus defined were used to compute stiffness in four extreme cases, which were the stiffest, and most compliant, consistent and variable subjects. All methods provided different stiffness measures for a given individual, but the between-method variations in stiffness were consistent across the four atypical subjects. The frequency-based method apparently overestimated the actual stiffness values, whereas double integrations' measures were more consistent. In double integrations, the choice of the integration constant and mathematical expression considerably affected stiffness values, as variations during hopping were more or less emphasized. Stating a zero centre of mass position at take-off gave more consistent results, and taking a weighted-average of the force or displacement curve was more forgiving to variations in performance. In any case, stiffness values should always be accompanied by a detailed description of their evaluation methods, as our results demonstrated that computational methods affect calculated stiffness.

1. Introduction

The human body is often modelled as a spring that is able to store and release elastic energy through its muscle–tendon unit structures. This mechanical simplification of the human body acting as a spring is regularly applied to cyclic or rebounding type motions observed during locomotion (e.g., walking, running and hopping) that depend on stretch-shortening cycle muscle actions. During these natural type of muscle actions, the pre-activated muscles are first stretched (eccentric action) before they are shortened (concentric action) with the eccentric–concentric combination enhancing the final (concentric action) performance (Komi, 2000).

When using the simple spring–mass model to describe human motion, the mechanical concept of stiffness is a key parameter of data analysis (Blum et al., 2009) and related to the ratio between a force and its corresponding displacement (Fig. 1). Stiffness is thereby the inverse of flexibility or compliance.

In its most macroscopic form, vertical stiffness is suggested to represent the overall body stiffness and defined as the ratio between the ground reaction force (GRF) and vertical displacement of the centre of mass (CoM). Leg stiffness, on the other hand, characterizes the stiffness of the lower-extremity and is described as the ratio between the GRF and leg length deformation (Cavagna, 1975; McMahon and Cheng, 1990). During locomotion, vertical stiffness is always greater than leg stiffness because changes in leg length surpass the vertical displacements of the CoM (Blickhan, 1989; Brughelli and Cronin, 2008; McMahon and Cheng, 1990). Although vertical and leg stiffness are not synonymous per se, the two are equivalent when leg length deformations are estimated from vertical jumps or hops (McMahon and Cheng, 1990; Serpell et al., 2012). Applied to a hopping task, the force in Fig. 1 is the external vertical (upwards) force from the ground support, whereas the displacement is the vertical (downwards) movement of the CoM during the ground contact.

There has been a rapid increase in the number of applied research studies documenting stiffness values for the lower-extremity (Hobara et al., 2012; Jacobs et al., 1996; Lloyd et al., 2012; Maquirriain, 2012; Moritz and Farley, 2006; Pruyn et al., 2012), with researchers suggesting that sufficient levels of stiffness

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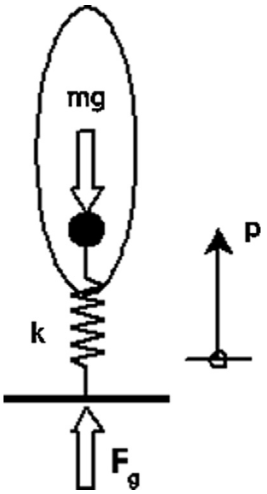

Fig. 1. Mechanical model for a human body of mass m in contact with the ground during a hop, with a mechanical spring representing the lower-extremity between the center of mass (CoM) and ground. The acting forces are the gravitational force mg, and the ground reaction force F_g. The position of the CoM is described by a vertical coordinate p of arbitrary origin, and the stiffness of the spring by a given constant k.

are required to optimize the utilization of the stretch-shortening cycle (Belli and Bosco, 1992; Kubo et al., 1999) and minimize the risk of musculoskeletal injury or re-injury (Maquirriain, 2012; Watsford et al., 2010). More specifically, high leg stiffness has been associated to a heightened risk of bony injuries (Granata et al., 2002; Williams et al., 2004), whereas low leg stiffness gives an increased susceptibility to soft tissue injuries (Butler et al., 2003; McMahon et al., 2012). Although the appropriate value of stiffness for performance and injury prevention has not yet been coined and depends on individual characteristics – i.e., sex, age, ethnicity and training background – the consistent use of a standard and valid computational method for measuring stiffness in research is important to attain a greater scientific merit and promote inferential and inductive reasoning in applied sciences (Borenstein and Hedges, 2009).

Without registrations of a vertical position coordinate during experimentation, double integrations and resonant frequencies are the bases for the two most common methods used to quantify leg stiffness from GRF registrations (Butler et al., 2003). In the first method, the vertical GRF-curve is integrated twice to determine the vertical displacement of the CoM during the ground contact period. An indeterminate integration constant is selected, with the different approaches for defining this integration constant being discussed further below. In the second method, the period of oscillation and body mass of the individual are used to calculate stiffness from the net-GRF, which subtracts the gravity force from the original GRF-curve. Near identical results from the double integration and resonant frequency methods have been reported (Granata et al., 2002), which are of equal validity when used in conjunction with the conceptualized leg spring and stretch-shortening models (Blum et al., 2009). However, there is a paucity of papers that report the actual stiffness values calculated from both approaches, using either one or citing that similar values were obtained if both were attempted (Granata et al., 2002). It is therefore challenging to contrast the different methods or make robust inferences from their respective results. Furthermore, the conventional methods used to quantify leg stiffness in clinical sciences are not always motivated by or verified against mechanical arguments.

The aim of this paper is to describe and contrast a range of computational methods used to quantify leg stiffness in humans from a double-legged repetitive hopping task, using only GRF registrations. A total of 13 different stiffness evaluation methods were tested and compared on a subset of data acquired from a larger cohort of healthy males. The implications and differences associated to the choice of the computational methods, integration constants, mathematical expressions and spring–mass model assumptions used to define stiffness are topics included in the discussion.

2. Methods

2.1. Subjects

After providing written informed consent, 40 healthy males participated in a multi-phase research project that evaluated several individual biomechanical characteristics, with only those pertaining to leg stiffness measurements from a double-legged repetitive hopping task reported here. The cohort had a mean $\pm$ standard deviation (SD) for age, height and mass of 30.4 ± 8.9 yr, 181.9 ± 7.0 cm and 77.3 ± 9.3 kg, respectively. The research protocol was pre-approved by the Regional Ethical Review Board and adhered to the *Declaration of Helsinki*. Individuals in good self-reported general health were included, and excluded when reporting a current or recent musculoskeletal injury, joint pathology or other medical condition that could limit performance of repeated double-legged hops. All subjects provided verbal and written informed consent prior to participation.

2.2. Experimental procedures

Each subject was familiarized with the experimental protocol and tested in a single laboratory-based session. After recording height using a telescopic measuring rod (Seca®, DE) and body mass on a calibrated force-plate (Kistler®, CH); each subject watched an instructional video that demonstrated the hopping task, performed a light-intensity 5-min warm-up on a cycling ergometer (Monark AB, SE), and practiced the experimental task under supervision and guidance from the examiner. During this specific pre-test familiarization period, the investigator provided corrective feedback designed to ensure that the hopping task was performed in an appropriate manner. The familiarization period was followed by 2 min of rest, after which data collection was performed.

2.3. Double-legged hopping task

For the evaluation of leg stiffness; each subject hopped barefooted using both legs in the middle of the calibrated force-pate (Kistler®, CH) with hands placed on hips, feet shoulder width apart and eyes directed forward. Subjects were instructed to keep their knees straight and land in a similar position to that of take-off from the force-plate (i.e., ankles plantar-flexed). Since contact time instructions can influence performance, stiffness values and stiffness regulation during hopping (Arampatzis et al., 2001; Hobara et al., 2007; Voigt et al., 1998), subjects were instructed to minimize ground contact times during hops, which implied minimal secondary movements in other joints.

The force-plate was zeroed prior to each trial and was used to collect GRF data at an 1000-Hz sampling frequency with the Kistler Measurement, Analysis and Reporting Software v.1.0.3 (S2P Ltd., SI). Each trial consisted of 33 successive hops performed at 2.2 Hz indicated audibly to subjects via the TempoPerfect© v.2.02a computerized metronome (NCH Software, AUS). Therefore, each hopping trial was meant to last approximately 15 s. If subjects failed to perform the hopping trial adequately – e.g., did not maintain the pace – the trial was disregarded and repeated after 2 min of rest. Only 5 subjects required a second attempt to achieve an acceptable performance.

2.4. Extraction of individual hops

The evaluation of leg stiffness was based on recorded GRF data with a constant time interval between registrations, $\Delta\tau = 0.001$ (s). The total registration contained N force values in a vector $\underline{F}$, with individual components F_i, treated as discrete values of the force variation $F = F(\tau)$, with τ as a time variable.

The vector $\underline{F}$ was first split into individual hops by identifying subsets of the vector with positive GRF values, interpreted as a sufficiently long range of components $i_1 \le i \le i_2$, where $F_{i_1} < \varepsilon$, and all other $F_i > \varepsilon$. These vectorial subsets were identified choosing a tolerance ε towards registration disturbances, set to $\varepsilon = 5$ (N) in this work. Each of the positive GRF sequences of a hop, with a time span denoted T, was collected in a vector $\underline{f}$ containing components f_i, with $0 \le i \le n_s$, and $n_s = (T/\Delta\tau) = i_2 - i_1$. A time $\tau = 0$ was thereby associated to the first component of each vector $\underline{f}$.