BETWEEN-DAY RELIABILITY OF LEG STIFFNESS MEASURED FROM GROUND REACTION FORCE REGISTRATIONS USING THREE DIFFERENT COMPUTATIONAL METHODS

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INTRODUCTION

In the context of sports and clinical biomechanics, the lower-extremity is often modelled as a spring that is able to store-and-release elastic energy during ground contact via the stretch-shortening cycle. The efficiency of the stretch-shortening cycle is often expressed in terms of stiffness, herein defined as the ratio between the ground reaction force (GRF) and displacement of the centre of mass (CoM).

Without registrations of a vertical position coordinate during experimentation, double-integration and resonant frequency are the bases for the two most common methods used to compute leg stiffness when only GRF registrations are available. [1] Although reasonably similar stiffness values have been suggested to result from these two methods, [2, 6] there is a paucity of papers that report the actual stiffness values computed from different computational approaches. Furthermore, although several studies have reported between-day reliability coefficients for leg stiffness measured during hopping, [3-5] these studies have not compared the reliability of measurements between computational methods on a unique data set. Consequently, it is a challenge to contrast the reliability of these different methods for computing leg stiffness from GRF registrations or make robust inferences from their respective results.

The aim of this paper is to contrast the results from and the between-day reliability of leg stiffness measured from GRF data using three different computational methods and a double-legged hopping task.

METHODS

Thirty active men (age: 31 ± 10 yr, height: 182 ± 6 cm, mass: 80 ± 8 kg) were tested on two occasions on two separate days after ethical approval was gained and subjects' gave written informed consent. Each subject was tested at the same time of day within a 3-day period. On the days of data collection, each subject watched a short instructional video that demonstrated the hopping task, performed a 5-min cycling warm-up on an ergometer (Monark AB, Sweden), and practiced performing the hopping task under supervision from the examiner. For the evaluation of leg stiffness, each subject hopped for 15-sec using both legs at a 2.2 Hz frequency, barefoot, knees straight, and hands on hips. All trials were completed on a multi-axial force-plate (Kistler®, CH) that collected GRF at a 1000 Hz using the Kistler Measurement, Analysis and Reporting Software version 1.0.3 (MARS™ , S2P Ltd., SI).

Three methods were used to compute leg stiffness from GRF registrations, which were performed in MATLAB® version 7.14.0.739 (The MathWorks, Inc., USA). In two methods, the GRF-curve was converted to vertical accelerations using the mass of the subject and gravitational acceleration (9.82 m·s^{-2}). The acceleration-curve was then doubly-integrated to yield velocity and position data based on central difference expressions with velocity values v evaluated halfway between stages for accelerations a and positions p, with a time step $\Delta\tau = 0.001$ s.

The initial position ($p_0 = p(0)$) integration constant was defined stating a zero vertical position of the CoM at the initial ground contact (i.e., when the GRF becomes positive). Out of four different reasonable choices for the initial velocity ($v_0 = v(0)$) integration constant, two were selected for this study. In one method, the integration constant was defined assuming a zero CoM position at take-off; and alternatively, the other method stated a zero CoM velocity at the maximal GRF.

In both double-integration techniques, leg stiffness was computed as the ratio between the maximal GRF and maximal vertical displacement of the CoM according to:

$$k = \frac{f_{max}}{p_{max}}$$

where k identifies leg stiffness, f_{max} the maximal GRF during ground contact, and p_{max} the maximal vertical (downwards) displacement of the CoM during ground contact.

The last method investigated was frequency-based and evaluated leg stiffness according to the following equation:

$$k = m\left(\frac{4\pi}{T^{+}}\right)^{2}$$

where m identifies the mass of the subject and T^{+} the duration of ground contact with a positive net (upward) force.

The expressions above describe three methods for evaluating leg stiffness for one single hop, using an isolated sequence of positive GRF data. To quantify the leg stiffness for one subject, each sequence of positive GRF that could correspond to one hop was isolated for each 15-sec hopping trial. Each of these isolated sequences provided one stiffness value representing one hop, which were then sorted in an ascending order. The middle 22 stiffness values within this order were then analysed to obtain one representative mean and standard deviation (± SD) value for each 15-sec trial. The selection procedure thereby removed outliers at both ends of the stiffness range, and gave a unique value computed from a representative 10-sec of hopping data.

Descriptive statistics are reported as mean ± SD values. Between-day reliability statistics computed for each method are intra-class correlation coefficients (ICCs) and typical error of measurements (in %), along with their 95% confidence limits [upper, lower]. Paired t-tests are used as bases for comparing the mean stiffness derived from the different methods, setting the statistical significance level at $P \leq 0.05$.

RESULTS

A summary of the descriptive and reliability statistics are presented in **Table 1**. In all individual cases; stiffness was greatest when computed using the frequency-based method (41 ± 8 $kN \cdot m^{-1}$), less when doubly-integrated under the zero CoM velocity assumption (39 ± 9 $kN \cdot m^{-1}$), and smallest when doubly-integrated under the zero CoM position assumption (35 ± 7 $kN \cdot m^{-1}$). These three methods had 0.91, 0.84, and 0.88 in ICC values; and 6.5%, 7.2%, and 9.4% in typical error of measurements, respectively. The stiffness computed using double-integration sating a zero CoM position at take-off was much lower than the stiffness computed using the other two methods ($P < 0.001$), with the latter two providing rather similar means ($P = 0.019$).

DISCUSSION

This study investigated three different methods for computing leg stiffness from a double-legged hopping task using GRF data only. We found that all three methods were highly reliable for computing leg stiffness, although each provided a different stiffness value for the same subject and task. The latter finding highlights the importance of describing in detail the method used for computing leg stiffness seeing how changing the computational method leads to varied levels of stiffness (i.e., 14% in this work). If several methods are trialled, the between-method difference should be quantified and reported to increase the possibility to make inferences from multiple study findings in research.

Out of the three computational methods investigated, the frequency-based one had the highest between-day ICC and lowest typical error of measurements for defining stiffness, suggesting that it was the most reliable. However, the method might have overestimated the actual leg stiffness of subjects considering that – in each case – this method computed the highest stiffness value. Inversely, the double-integration method that stated a zero position of the CoM at take-off might have underestimated stiffness, as it always computed the lowest stiffness in each subject. Nevertheless, for setting the initial velocity integration constant, doubly-integrating a GRF-curve under a position vs. velocity criterion was more reliable and appears to be a better choice.

CONCLUSIONS

Our results clearly demonstrate that the choice of the computational method influences the leg stiffness value resulting from a double-legged hopping task. Scientists are hence encouraged to carefully consider and acknowledge that the spring-mass model assumptions and integration constants selected affect stiffness computations.

In doubly-integrated approaches, we recommend stating a zero CoM position at take-off in opposition to a zero CoM velocity at peak GRF to achieve higher reliability and consistency in results. In any case, leg stiffness values should always be accompanied by a detailed account of their evaluation methods. The standardization of methods used in science to determine leg stiffness from GRF registrations is highly desirable, and should be made a common goal.

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Table 1. Mean ± SD of stiffness computed from GRF data of 30 subjects performing a double-legged hopping task. Day 1, day 2, and between-day differences in stiffness are reported for three different computational methods. The measures of reliability for each method are reported with 95% confidence limits [upper limit, lower limit].

Computational	**Stiffness**			**Reliability**	
method	**Day 1**	**Day 2**	**Difference**	**ICC**	**TEM (%)**
M_P	35.4 ± 6.6	34.5 ± 7.3	-0.8 ± 3.6	0.88 [0.76, 0.94]	7.2 [5.8, 9.7]
M_V	39.2 ± 8.3	38.0 ± 9.4	-1.2 ± 5.1	0.84 [0.69, 0.92]	9.4 [7.5, 12.6]
M_F	41.0 ± 7.8	40.1 ± 8.8	-0.9 ± 3.7	0.91 [0.81, 0.95]	6.5 [5.2, 8.8]
All methods	**38.5 ± 2.9**	**37.6 ± 2.8**	**-1.0 ± 0.2**	**0.87 ± 0.03**	**7.7 ± 1.5**

GRF, ground reaction force. ICC, intra-class correlation. SD, standard deviation. TEM, typical error of measurements.

M_P: Double-integration of the GRF-curve that assumes a zero position of the centre of mass at take-off

M_V: Double-integration of the GRF-curve that assumes a zero velocity of the centre of mass at maximal GRF

M_F: Frequency-based method that considers the duration of ground contact