Journal of Biomechanics 64 (2017) 253–257

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Short communication

A comparison and update of direct kinematic-kinetic models of leg stiffness in human running

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ARTICLE INFO

Article history:
Accepted 25 September 2017

Keywords:
Running
Stiffness
Kinematics
Kinetics

ABSTRACT

Direct kinematic-kinetic modelling currently represents the "Gold-standard" in leg stiffness quantification during three-dimensional (3D) motion capture experiments. However, the medial-lateral components of ground reaction force and leg length have been neglected in current leg stiffness formulations. It is unknown if accounting for all 3D would alter healthy biologic estimates of leg stiffness, compared to present direct modelling methods. This study compared running leg stiffness derived from a new method (multiplanar method) which includes all three Cartesian axes, against current methods which either only include the vertical axis (line method) or only the plane of progression (uniplanar method). Twenty healthy female runners performed shod overground running at 5.0 m/s. Three-dimensional motion capture and synchronised in-ground force plates were used to track the change in length of the leg vector (hip joint centre to centre of pressure) and resultant projected ground reaction force. Leg stiffness was expressed as dimensionless units, as a percentage of an individual's bodyweight divided by standing leg length (BW/LL). Leg stiffness using the line method was larger than the uniplanar method by 15.6%BW/LL ($P < .001$), and multiplanar method by 24.2%BW/LL ($P < .001$). Leg stiffness from the uniplanar method was larger than the multiplanar method by 8.5%BW/LL (6.5 kN/m) ($P < .001$). The inclusion of medial-lateral components significantly increased leg deformation magnitude, accounting for the reduction in leg stiffness estimate with the multiplanar method. Given that limb movements typically occur in 3D, the new multiplanar method provides the most complete accounting of all force and length components in leg stiffness calculation.

1. Introduction

Leg stiffness is thought to be an important control parameter in locomotion (Seyfarth et al., 2002; Shen and Seipel, 2015a), and is defined by the ratio of peak ground reaction force (GRF) and the change in leg length in the stance phase (Coleman et al., 2012). Presently, there are many methods of calculating the constituent components of leg stiffness (i.e. force and length components), which may produce differences in estimates of healthy biologic leg stiffness by up to 80% (Coleman et al., 2012). Evidently, the choice of leg stiffness methods has implications for intervention design (Beck et al., 2017), and the development of control theories for locomotion (Seyfarth et al., 2002; Shen and Seipel, 2015a).

The direct method of measuring leg stiffness during three dimensional (3D) motion capture represents the current "Gold-standard" (Coleman et al., 2012), as it minimizes assumptions made when modelling the force and length components of leg stiffness. Currently, only the magnitudes of the vertical components of leg length and GRF (Farley and Gonzalez, 1996), or the sagittal plane scalar magnitudes have been used (Coleman et al., 2012). It has been implicitly argued that only including the sagittal plane scalar magnitudes into stiffness calculation sufficiently provide the most valid estimate of leg stiffness in running (Coleman et al., 2012), although this has not been formally verified. The medio-lateral (ML) component of GRF can reach up to 12% of vertical GRF (Cavanagh and Lafortune, 1980), and the ML foot displacement can differ between laterality by up to 0.05 m in amputees running (Arellano et al., 2015).

Given that human gait typically involve limb movements and GRF in 3D, accounting for the ML force and length components will provide the most complete method of leg stiffness calculation. However, it is unknown if a method which accounts for force and length components in all 3D would produce statistically and clinically relevant differences from currently employed direct stiffness methods (Coleman et al., 2012; Farley and Gonzalez, 1996).

The primary aim of this study was to investigate how estimates of healthy biologic leg stiffness in human running differs between

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https://doi.org/10.1016/j.jbiomech.2017.09.028

three different direct leg stiffness modelling methods, when different number of dimensions were accounted for in the constituent force and length components. In this paper we termed the method using only the vertical axis component as the "line method", the vertical and anterior-posterior (AP) axes as the "uniplanar method" and all three axes as the "multiplanar method".

2. Methods

2.1. Design

This is a secondary analysis of running data conducted on 20 healthy female recreational runners (25.1 (6.0) years, 1.66 (0.07) m, 61.3 (8.9) kg, 14 rearfoot strike and 6 forefoot strike patterns). These participants were originally recruited for an experiment on rigid hip taping and running kinematics. The study was approved by Curtin University's Human Research Ethics Committee (PT022/2014), and all participants provided written informed consent.

2.2. Running protocol

Participants performed shod overground running at a controlled speed of 5.0 m/s (±10%), across three in-ground force platforms (3 m in total distance). Participants were given a 20 m run up to achieve the required speed, and a 10 m tail off for deceleration. Marker trajectories were collected using an 18 camera motion capture system at 250 Hz (Vicon T-series, Oxford Metrics, UK), whilst synchronized GRF were collected at 2000 Hz (AMTI, Watertown, MA). A 20 N force platform threshold was used to define initial and terminal contact.

2.3. Biomechanical model

A seven segment biomechanical model based on a previous study was used (Liew et al., 2016). The geometric and inertial characteristics of the biomechanical model was defined using Visual 3D (C-motion, Germantown, MD) default routines (Dempster, 1955; Hanavan, 1964). Marker trajectories and GRF were filtered at 15 Hz (fourth ordered, zero-lag, Butterworth).

2.4. Leg stiffness methods

First, the leg was represented by a 3D (coordinates X – mediolateral, Y – anteriorposterior, Z – vertical) vector from the right hip joint centre (HJC) to the centre of pressure (COP) of the right foot. For the line method, the leg vector was defined by the vertical height of the HJC to the COP (Z-axis). For the uniplanar method, leg vector was defined by the YZ sagittal plane by setting the mediolateral component to zero for all data frames. For the multiplanar method, leg vector was defined by all three axes. For each method, the resultant length of the leg vector was used as the denominator for leg stiffness calculation.

For the line method, the vertical GRF magnitude was used to calculate leg stiffness. For the uniplanar method, a 2D GRF vector was created by setting the mediolateral component of the GRF to zero for all data frames. For the multiplanar method, the original 3D GRF vector was used. For both uniplanar and multiplanar methods, the respective GRF vector was projected onto the respectively dimensioned leg vector by taking the dot product of the GRF vector by the unit vector of the leg. No projection of the GRF is needed for the line method.

For all methods, leg stiffness was calculated by taking the ratio between the peak magnitude of the resultant projected GRF, and the resultant change in length of the leg vector. Change in leg length was defined by the difference between length at initial contact and length at peak resultant projected GRF. The time of peak projected GRF was specific to each method.

Leg stiffness was expressed as dimensionless units (%BW/LL) (dividing raw values to bodyweight over static standing leg length) (Liew et al., 2017). The group mean normalizing factor was 759.8 N/m. GRF was expressed as a %BW, whilst leg length was expressed as a %LL.

2.5. Statistical analyses

A linear mixed model was used to analyse the effect of the independent variable ("Method") on leg stiffness, peak resultant GRF, and leg length change. Post-hoc analysis using Tukey's pairwise comparison was used. This was performed in R software (v 3.2.5) within RStudio (v0.99.902, RStudio, Inc.) (Hothorn et al., 2008 ; Pinheiro et al., 2016).

3. Results

3.1. Leg stiffness

All three methods differed in the magnitude of derived leg stiffness ($F_{2,254} = 69.13$, $P < .001$) (Table 1, Fig. 1). Leg stiffness using the line method was larger than the uniplanar method by 15.6%BW/LL ($P < .001$), and the multiplanar method by 24.2%BW/LL ($P < .001$) (Table 1, Fig. 1). Leg stiffness from the uniplanar method was larger than the multiplanar method by 8.5%BW/LL ($P < .001$) (Table 1, Fig. 1).

3.2. Ground reaction force and leg length

Resultant projected GRF did not differ between all three methods ($F_{2,254} = 1.967$, $P = .1421$) (Table 1, Fig. 2b). All three methods differed in the magnitude of resultant leg length change ($F_{2,254} = 19.319$, $P < .001$) (Table 1, Fig. 2f). Leg length change using the line method was smaller than the uniplanar method by 0.029%LL ($P = .031$), and the multiplanar method by 0.043%LL ($P = .045$) (Table 1, Fig. 2f). Leg length change from the uniplanar method was smaller than the multiplanar method by 0.014%LL ($P = .014$) (Table 1, Fig. 2f).

4. Discussion

The aim of this study was to investigate if accounting for all 3D within leg stiffness modelling could significantly alter healthy biologic estimates of leg stiffness, compared to current direct modelling methods. For a 60 kg adult running at 5.0 m/s, the new multiplanar method resulted in 6.5 kN/m smaller leg stiffness compared to the current "Gold-standard" uniplanar method. Given that a difference in leg stiffness by approximately 1 kN/m occurred after an exhaustive maximal run (Hayes and Caplan, 2014), a difference of 6.5 kN/m may have important clinical and scientific implications.

Across this study and that of another (Liew et al., 2017), leg stiffness while running at 5 m/s varies between 34%BW/LL to 39% BW/LL (25–29 kN/m) using the "Gold-standard" uniplanar method. Surprisingly, the original paper which developed the current direct uniplanar method reported much lower leg stiffness values of 13.9 kN/m (Coleman et al., 2012). It may be that the mean velocity in Coleman et al. (2012) was much slower that of this study, although a range of velocities (2–6.5 m/s) was used. However, a separate study which had participants running at 3.3 m/s reported stiffness values using the uniplanar method of 35%BW/LL (Silder et al., 2015). Differences in stiffness values between studies may be