Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

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

The effectiveness of scaling procedures for comparing ground reaction forces

Christopher D. Stickley [a,b], Samantha N. Andrews [a,*], Elizabeth A. Parke [c], Ronald K. Hetzler [a]

[a] Department of Kinesiology and Rehabilitation Sciences, University of Hawaii, 1337 Lower Campus Road, Honolulu, HI 96822, United States
[b] Department of Anatomy, Biochemistry and Physiology, John A Burns School of Medicine, University of Hawaii, 651 Ilalo St, Honolulu, HI 96813, United States
[c] Department of Kinesiology, California State University, Northridge, 18111 Nordhoff St, Northridge, CA 91330, United States

ARTICLE INFO

Article history:
Accepted 19 June 2018
Available online xxxx

Keywords:
Kinetics
Ground reaction force
Scaling
Allometric scaling
Gait

ABSTRACT

Various scaling methods are used when attempting to remove the influence of anthropometric differences on ground reaction forces (GRF) when comparing groups. Though commonly used, ratio scaling often results in an over-correction. Allometric scaling has previously been suggested for kinetic variables but its effectiveness in partialing out the effect of anthropometrics is unknown due to a lack of consistent application. This study examined the effectiveness of allometric scaling vertical, braking and propulsive GRF and loading rate for 84 males and 47 females while running at 4.0 m/s. Raw, unfiltered data were ratio scaled by body mass (BM), height (HT), and BM multiplied by HT (BM∗HT). Gender specific exponents for allometric scaling were determined by performing a log-linear (for BM and HT individually) or log-multilinear regression (BMHT). Pearson productmoment correlations were used to assess the effectiveness of each scaling method. Ratio scaling by BM, HT, or BM∗HT resulted in an over-correction of the data for most variables and left a considerable portion of the variance still attributable to anthropometrics. Allometric scaling by BM successfully removed the effect of BM and HT for all variables except for braking GRF in males and vertical GRF in females. However, allometric scaling for BMHT successfully removed the effect of BM and HT for all reactionary forces in both genders. Based on these results, allometric scaling for BMHT was the most appropriate scaling method for partialing out the effect of BM and HT on kinetic variables to allow for effective comparisons between groups or individuals.

1. Introduction

Kinetic running gait data are often scaled to remove the influence of anthropometric differences between subjects and allow for comparison of groups when, for example, trying to identify injury risk factors. The scaling practice of simply dividing an outcome variable by a selected anthropometric variable, commonly referred to as ratio scaling, is widely used in biomechanics research due to the positive correlation between kinetic and anthropometric variables, including body mass (BM) and height (HT) (Moisio et al., 2003). Mullineaux et al. (2006) reported previously that ratio scaling controlled for all but approximately one percent of the variance in ground reaction forces (GRF) attributable to BM. Based on these findings, the authors concluded that ratio scaling was adequate for removing the influence of BM on GRF, allowing for improved accuracy when comparing subjects and groups of differing body size (Mullineaux et al., 2006).

However, there are well understood limitations to ratio scaling for body size. Ratio scaling generally results in an over-correction, providing smaller participants with an advantage and resulting in a negative correlation between the scaled variable and BM (Winter, 1992, Hetzler et al., 2011; Stickley et al., 2013). Additionally, Wannop et al. (2012) suggested that the lack of true linear relationship between kinetic and anthropometric variables, specifically BM, limits the effectiveness of ratio scaling.

One proposed alternative to ratio scaling involves the use of nonlinear power exponents, also called power curve normalization, though this approach has been more widely utilized in the field of exercise physiology (Mullineaux et al., 2006; Wannop et al., 2012). Referred to as allometric scaling in exercise physiology research, indications for this scaling method are based on the assumption that the relationship between an outcome variable and an anthropometric variable (such as BM) is curvilinear (Vanderburgh et al., 1995). Allometric scaling is based on the relationship $y = ax^b$, where a and b are constants, y is the outcome variable (e.g. GRF)

* Corresponding author at: 4725 Bougainville Drive #365, Honolulu, HI 96818, United States.
E-mail address: sandrews@hawaii.edu (S.N. Andrews).

https://doi.org/10.1016/j.jbiomech.2018.06.021
0021-9290/© 2018 Published by Elsevier Ltd.

and x is the body size variable (Vanderburgh and Dooman, 2000). Allometric scaling yields an outcome variable, y, relative to a scaling variable, x, that is free of the undue influence of the scaling variable: for example, Allometrically scaled GRF = GRF/BM^b. In other words, the independent effects of the scaling variable on the outcome variables are partialed out (Vanderburgh et al., 1996), as indicated by a correlation between the scaled variable and BM that approaches zero. Significant remaining correlations indicate that the independent effects of the scaling variable on the outcome variable have not been adequately partialed out. The scaling process is similar to ratio scaling, where the outcome variable is divided by the scaling variable. However, the inclusion of the "b" exponent on the scaling variable acknowledges the relationship between the outcome and scaling variables as curvilinear. A full description of how the "b" exponents are derived has been described previously (Vanderburgh et al., 1995; Batterham and George, 1997).

Based on the limited research examining allometric scaling of kinetic variables, the advantages of using this scaling method over others is unclear. Conclusions drawn from previous studies regarding the value of allometric scaling for kinetic variables vary, possibly due to the lack of consistent application of accepted procedures for allometric scaling, including separation of data by gender (Vanderburgh, 1998), the use of log–log transformed data (Batterham and George, 1997; Vanderburgh, 1998) and lack of proper regression diagnostics to determine the appropriateness of the derived models (Batterham and George, 1997). Additionally, though allometric scaling has been shown to effectively remove the influence of BM on vertical and anterior/posterior GRF and loading rate in the limited biomechanical studies investigating this technique (Mullineaux et al., 2006; Wannop et al., 2012), these studies have not examined the role of additional anthropometric measures, such as height, on kinetic variables. The use of ratio or allometric scaling methods that account for body mass, as well as height, may provide for more valid comparison between subjects or groups of varying body size. Therefore, the purpose of this study was to evaluate the effectiveness of ratio and allometric scaling for body mass and height on kinetic variables including vertical ground reaction force (vGRF), propulsive ground reaction force (pGRF), braking ground reaction force (bGRF) and loading rate. These variables of interest were chosen based on their inclusion in a previous examination of scaling methods (Mullineaux et al., 2006). The following hypotheses were assessed: (1) Allometric scaling will be more effective than ratio scaling in partialing out the effects of BM on these variables of interest, (2) the independent effects of HT on these outcome variables will not be removed when scaling for BM and (3) allometric scaling for both BM and HT will most effectively remove the effect of anthropometric variables on the kinetic variables of interest.

2. Methods

Eighty-four males (age: 23 ± 5 years; height: 178 ± 7.9 cm; BM: 77.6 ± 12.4 kg; BMI: 24.6 ± 3.3) and forty-seven females (age: 26 ± 7 years; height: 164.4 ± 7.8 cm; BM: 62.5 ± 9.1; BMI: 23.1 ± 3.1) were recruited from a university population. Inclusionary criteria included (1) no history of a current or medical condition that prevented them from participation in physical activity, (2) no lower extremity surgery within the past six months and (3) not suspected to be pregnant. No attempt was made to control for training status, diet, or activity level in recruited participants. A university institutional review board for studies involving human subjects approved all study procedures for collection of the resulting data.

Participants were asked to report to the laboratory in their regular physical activity clothing and non-standardized personal running shoes. Kinetic data were recorded at 960 Hz using an AMTI force plate (Advanced Mechanical Technology Incorporated, Boston, Massachusetts, USA) embedded flush with the runway. Speedtrap II (Brower Timing Systems, Draper, Utah, USA) infrared sensors were placed four meters apart on the middle third of the runway to collect velocity. Three successful trials were collected for the right leg, with a successful trial defined as running a prescribed velocity (4.0 $m \cdot s^{-1}$ ± 10%) (Crossley et al., 1999; Hreljac et al., 2000; Bennell et al., 2004) and the entire foot landing on the force plate without apparent targeting. Kinetic data were analyzed as raw, unfiltered data using Visual 3D (C-Motion Inc., Germantown, Maryland).

2.1. Statistical analysis

Kinetic variables included peak values for vGRF, pGRF and bGRF, as well as loading rate. Ensemble averages for peak values from three successful trials were used for analysis. Loading rate was calculated as the time derivative of vGRF from initial contact to peak vGRF (Loading Rate = peak vGRF/time to peak) (Keller et al., 1996). Individual ratio scaling procedures were performed by dividing each kinetic variable by (1) body mass (BM), (2) height (HT) and (3) body mass multiplied by height (BM*HT). All variables were allometrically scaled by body mass (BM), height (HT) and body mass combined with height (BMHT). Following the procedures of Vanderburgh et al. (1995), a log-linear regression was used to develop the allometric exponents ("b") for separately comparing BM and HT for each outcome variable by gender. In order to allometrically scale for BMHT, a multi-linear regression of the log transformed data was performed to determine BM and HT specific exponents. Regression diagnostics were performed to identify the appropriateness of the scaling, including the Kolmogorov-Smirnov test to determine normality of residuals and the Breusch-Pagan test to evaluate homoscedasticity (Vanderburgh et al., 1996; Vanderburgh, 1998, Hetzler et al., 2011, Stickley et al., 2013). Allometrically scaled values for each variable of interest were calculated using the previously described formula (y/x^b) where "b" is the derived exponent for each variable from the log-linear regression. Raw, ratio scaled and allometrically scaled values for each outcome variable were correlated to each anthropometric variable to determine the extent to which the independent effect of the anthropometric variables had been partialed out, with a correlation closer to zero being determined preferable. The square of each correlation was calculated to determine the percent of the variance in each outcome variable that could still be attributed to the anthropometric variable after the scaling procedure, with decreased R^2 values indicating superior performance of the scaling procedure in controlling for the effect of the anthropometric variable on the outcome variable. The Predicted Residual Sum of Squares (PRESS) procedure was used to evaluate external validity of the derived allometric exponents (Holiday et al., 1995; Stickley et al., 2013). Mean and standard deviation for each outcome variable, Pearson product-moment correlations and 95% confidence intervals were generated for each scaling procedure. A significant alpha level was designated as $p \leq 0.05$ for all analyses.

3. Results

Means and standard deviations for raw, ratio scaled and allometrically scaled output variables are presented in Table 1. Correlations between raw outcome variables and anthropometrics for males and females are presented in Table 2. All raw reactionary forces for males and females were significantly positively correlated with BM and BM multiplied by HT (BM*HT) ($p < 0.001$). With the exception of bGRF for males ($p = 0.11$), HT was also