Journal of Biomechanics 49 (2016) 479–483

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Short communication

The high frequency component of the vertical ground reaction force is a valid surrogate measure of the impact peak

Tim Blackmore [a,*], Richard W. Willy [b], Mark W. Creaby [a]

[a] School of Exercise Science, Australian Catholic University, Brisbane, Australia
[b] Department of Physical Therapy, College of Allied Health Sciences, East Carolina University, Greenville, NC, USA

ARTICLE INFO

Article history:
Accepted 14 December 2015

Keywords:
Proxy
Running
Rear-foot strikers

ABSTRACT

Identification of the impact peak (IP) from the vertical ground reaction force (vGRF) is required to calculate indices of impact loading during running. The IP, however, is not always clearly discernible. Previous researchers have estimated the timing of the IP using surrogate methods, the most common of which is a set time point of 13% stance (TPS). Information contained within the high frequency (HiF) component of the vGRF may also have a utility as a surrogate measure, but the validity of either approach is currently unknown. The purpose of this study is to evaluate the criterion validity for a newly proposed HiF method and the previously used TPS method against a criterion measure for a group of rear-foot striking runners. Fifty participants ran at a standardized speed ($3.3\ m \cdot s^{-1}$) on an instrumented treadmill. Five consecutive stance phases were analyzed for the participant's dominant limb. Bland–Altman was used to assess agreement between the criterion method and each surrogate method. Good agreement of the HiF and TPS methods with the criterion method indicate that both methods are likely to be valid surrogate approaches to estimate vGRF impact loading indices. For all impact loading indices, smaller bias and limits of agreement (LOA) were observed with the HiF method when compared to the TPS method. Therefore, it is concluded that the HiF method should be used in preference to the TPS method when it is available.

1. Introduction

When running, rear-foot strikers typically demonstrate an impact peak (IP) in the vertical ground reaction force (vGRF) within the first 50 ms of stance (Nigg et al., 1995). Identification of the IP is required to determine its magnitude and timing, and to calculate loading rate. These measures, calculated from the early part of stance (Nigg et al., 1995) are widely studied and have been linked with both injuries (Noehren et al., 2013; Zadpoor and Nikooyan, 2011) and performance (Munro et al., 1987) in rear-foot striking runners. Not all runners exhibit a discernible IP, and gait modifications, such as an increase in running cadence, reduce the incidence of the IP (Heiderscheit et al., 2011). Thus directly calculating these indices of impact loading is not always possible. To address this, researchers have utilized alternative methods to predict the timing of the IP where one is not clearly discernible (Goss and Gross, 2013; Lieberman et al., 2010; Samaan et al., 2014; Willy et al., 2008).

When an IP was present in some trials, but not others, Lieberman et al., (2010) used the timing of the IP for each participant from the IP observed in the participants' other trials. This was then used as a surrogate for the timing of the IP in trials without a discernible IP. This method, however, relies on the IP being present in at least some trials. An alternative method presented by Willy et al. (2008), and used by others (Samaan et al., 2014), does not require the IP in any trials. Based on the timing of the IP, Willy et al. (2008) concludes that a set time point of 13% stance (TPS) in the absence of an IP could be used. However, this approach does not account for changes in the timing of the IP, which may occur between individuals and between conditions. While the relationship between the time of the IP and the TPS method has been evaluated, the validity of this approach is not known.

Although a clearly discernible IP in the vGRF may not be present, characteristics of this peak appear to be present in the high frequency signal of the vGRF. This is visible when the vGRF is separated into its high (HiF) and low (LoF) frequency components via the frequency domain (Shorten and Mientjes, 2011). Once separated, the LoF components (0 Hz to 10 Hz) resemble a half sinusoidal wave with a peak that appears to coincide with that of the passive peak of the vGRF, whereas the HiF components (10 Hz to ~50 Hz) are characterized primarily by a single peak, which

* Corresponding author. Tel.: +61 7 3623 7692.
E-mail address: Tim.Blackmore@acu.edu.au (T. Blackmore).

http://dx.doi.org/10.1016/j.jbiomech.2015.12.019
0021-9290/

Nomenclature

AVLR	average vertical loading rate
BW	bodyweight
cm	centimeter
HiF	high frequency
Hz	Hertz
IP	impact peak
IVLR	instantaneous vertical loading rate
kg	kilogram
km	kilometer
LOA	limits of agreement
LoF	low frequency
m	meter
ms	millisecond
N	Newton
s	second
SD	standard deviation
TPS	thirteen percent (13%) stance
vGRF	vertical ground reaction force

occurs early in stance and appears to coincide with the IP of the vGRF. Therefore, identification of the timing of the HiF peak may provide a more appropriate surrogate measure for identifying the timing of the IP and thus other indices of impact loading, such as loading rate. Whilst in theory the peak in the HiF component of the vGRF may coincide with the IP, the agreement between these two approaches has not been evaluated. If they coincide, this may provide a valid estimation of impact loading indices in participants where a discernible IP does not exist.

The purpose of this study was to evaluate the criterion validity for the HiF method and a previously used surrogate measure (TPS) against the criterion measure for the determination of the IP for a group of rear-foot striking runners. We then sought to assess the criterion validity across these various methods for the calculation of average vertical loading rate (AVLR) and instantaneous vertical loading rate (IVLR) in the same group of runners.

2. Methods

2.1. Participants

Fifty runners participated in this study (Table 1). The study was approved by the East Carolina University Human Subjects Research Board. Written and verbal consent were obtained from all participants. Inclusion criteria for study participation were: rear-foot strikers, consistently running at least 10 km/week for at least the previous 6 months, free of lower extremity injuries for the past three months and no previous lower extremity surgery.

2.2. Procedures

Following an eight-minute, self-paced treadmill accommodation period, GRF data were acquired (MotionMonitor, Innovative Sports, Chicago, Ill, USA) as participants ran at a standardized speed ($3.3\ m \cdot s^{-1}$) on an instrumented treadmill (TM-09, Bertec Corp., Worthington, OH, USA) with the integrated force plate sampling at 1000 Hz. Five consecutive stance phases were analyzed independently for the right and left legs.

2.3. Data analysis

The threshold for foot-strike and toe-off was set at 20 N. Data were separated into individual stance phases using a custom MATLAB script (version 7.10.0.499, Mathworks, Cambridge, UK) and low-pass filtered at 50 Hz (Butterworth, 4th order). The HiF and LoF signals were isolated using a custom MATLAB script (Supplementary Material 1). The vGRF for each stance phase was spectrally decomposed into the frequency domain using the discrete Fourier transform. The HiF components of the signal were separated from LoF components by isolating frequencies equal to or greater than 10 Hz (i.e. 10 Hz to ~50 Hz), while LoF components were constructed from the remaining lower frequencies (Shorten and Mientjes, 2011). Both HiF and LoF signals were recomposed into the time domain using the inverse Fourier transform to form two new signals (Fig. 1).

The IP, IVLR and AVLR were calculated from the vGRF and form the criterion variables for this study. The IP was defined as the first peak in the vGRF (within the first 50 ms of stance) (Nigg et al., 1995). Both IVLR and AVLR were calculated between 20% and 80% of the period between foot-strike and the occurrence of the IP (Milner et al., 2006). The IVLR was the steepest point in the slope of the vGRF during this period calculated using the first central difference method. The AVLR was calculated as the average slope in the vGRF between the 20% and 80% points. For each participant, a minimum of three trials with a clear IP were required to be included in the IP group for further analyses. Those without a clear IP in at least three trials were allocated to the NO IP group and were subsequently excluded from further analyses.

In the IP group, the timings of the peak magnitude of the HiF loads and of TPS were identified and used to calculate the surrogate measures in the same way as those used for the criterion measures. The surrogate timings and the corresponding magnitude from the vGRF was used to calculate the surrogate measures to form three new variables (IP, IVLR and AVLR) for each surrogate method (HiF & TPS).

2.4. Statistical analysis

All data were normally distributed except for age (Supplementary Material 2). An alpha level was set at 0.05 (SPSS v.20, IBM Corp, Armonk, NY). Criterion validity was examined in the IP group by assessing the agreement between the criterion approach and the two surrogate methods using the Bland–Altman method (Bland and Altman, 2010) in SigmaPlot (v.12, Systat Software, San Jose, CA). This was performed by plotting the difference for each dependent variable between the criterion and surrogate method against the mean data for the criterion and surrogate methods.

3. Results

Forty-two participants were assigned to the IP group, and 8 to the NO IP group. Mean demographic data were similar between the IP and NO IP groups.

For the right leg data, when compared to the criterion measure using Bland–Altman, no obvious relationship between the difference and the mean was observed for the IP, AVLR or IVLR using either surrogate method (Fig. 2). Both approaches showed a bias towards a lower mean in all but one case: the IVLR in the HiF

Table 1
Mean (SD) participant demographics for the IP group and the NO IP group.

	Age (yrs)		Running volume (km/week)		BMI (kg/m^2)		Height (m)		Mass (kg)		Male:Female
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	
IP group (n=42)	21.6	20.9–22.3	58.5	44.3–72.6	22.5	21.6–23.4	173.2	170.3–176.1	68	64.0–72.0	24:18
NO IP group (n=8)	24.4	20.7–28.3	57.7	31.5–83.8	23.5	21.7–25.3	176.1	163.8–188.3	72.9	64.0–81.7	2:6

BMI=body mass index.