Symbols

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

Introduction

When running, rear-foot strikers typically demonstrate an impact peak (IP) in the vertical ground reaction force (vGRF) within the first 50ms 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

58 is separated into its high (HiF) and low (LoF) frequency components via the frequency
59 domain (Shorten and Mientjes, 2011). Once separated, the LoF components (0Hz to 10Hz)
60 resemble a half sinusoidal wave with a peak that appears to coincide with that of the passive
61 peak of the vGRF, whereas the HiF components (10Hz to ~50Hz) are characterized primarily
62 by a single peak, which occurs early in stance and appears to coincide with the IP of the
63 vGRF. Therefore, identification of the timing of the HiF peak may provide a more
64 appropriate surrogate measure for identifying the timing of the IP and thus other indices of
65 impact loading, such as loading rate. Whilst in theory the peak in the HiF component of the
66 vGRF may coincide with the IP, the agreement between these two approaches has not been
67 evaluated. If they coincide, this may provide a valid estimation of impact loading indices in
68 participants where a discernible IP does not exist.

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

74 **Methods**

75 ***Participants***

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

81 ***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.

Data analysis

The threshold for foot-strike and toe-off was set at 20N. 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 50Hz (Butterworth, 4^{th} 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 10Hz (i.e. 10Hz to ~50Hz), 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 (Figure 1).

**** Figure 1 near here ****

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 50ms 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 & AVLR) for each surrogate method (HiF & TPS).

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.

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.

**** Table 1 near here ****

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 (Figure 2). Both approaches showed a bias towards a

lower mean in all but one case: the IVLR in the HiF method. In all measures the biases and limits of agreement (LOA) were smaller with the HiF method (Table 2). Analyses of the left leg data were consistent with the findings for the right leg (Supplementary Material 3 & 4).

**** Table 2 near here ****

**** Figure 2 near here ****

Discussion

The focus of this study was to assess the criterion validity of two surrogate methods to determine vGRF IP characteristics. Bland and Altman (2010) state that if the values that fall within the LOA are not clinically important then the methods can be used interchangeably, with the decision as to what is important being clinical and not statistical. Broadly considering our findings, it would appear that both methods performed well due to the small bias and LOA, but as these measures were lower in the HiF method when compared to the TPS method, it would suggest that the HiF method was superior. The validity of either surrogate approach must be made in the context of the population, or populations, studied (Bland and Altman, 2010), and therefore it is not possible to broadly conclude whether either surrogate method has acceptable agreement with the criterion method.

One approach to evaluating the validity of the surrogate methods would be to consider the error introduced by the use of the surrogate (characterized by the LOA) relative to the variation normally observed within the studied population (e.g. SD). For example, in the running literature indices of impact loading are frequently characterized in the study of lower limb stress fractures. Examination of this literature indicates typical IP magnitudes of approximately 2BW, with a within group SD ranging from 0.13BW to 0.45BW (Zadpoor and Nikooyan, 2011). Given a normal distribution, the LOA suggest that 95% of the time we can expect a bias of between -0.06BW and -0.01BW for the HiF method (an error of up to

153 3.64%) and between -0.21BW and 0.07BW for the TPS method (an error of up to 12.73%).
154 Thus, the LOA for the HiF method do not overlap the smallest within group SD suggesting
155 that it could be considered valid for use in this population. The LOA associated with the TPS
156 method however, do overlap suggesting that it may not be a valid approach. Similarly, in
157 considering the validity of the two approaches for estimating loading rates, the smallest
158 within group SD from the literature (Zadpoor and Nikooyan, 2011) for both the AVLR
159 (15.03BW·s^{-1}) and IVLR (17.33BW·s^{-1}) are greater than the LOA for both surrogate methods
160 suggesting that both methods are valid in this population. For both AVLR and IVLR, the
161 LOA are less when using the HiF method, suggesting that this approach is more appropriate
162 when compared to the TPS method.

163 Given the IP is a summation of both the HiF and LoF components the IP is always delayed
164 when compared to the timing of the HiF peak (Supplementary Material 5A). A visual
165 examination of the IP magnitude highlights that the HiF method consistently underestimates
166 the IP magnitude (Supplementary Material 5B), but the TPS method is less systematic. This
167 systematic underestimation is attributed to the use of the HiF method. As the timing of the
168 HiF signal is calculated from the acquired vGRF, and not from a time relative value such as
169 TPS, it responds more accurately to changes in the timing of the IP. Ultimately, correct
170 identification of the IP enables a more accurate estimation of AVLR, but is less pertinent to
171 IVLR due to the nature of its instantaneous calculation. As the IVLR is defined as the
172 steepest point in the slope of the vGRF between 20% and 80% of the time between heel-
173 strike and the IP, small changes in identification of the time of the IP will only alter the start
174 and end point of the window in which the IVLR is calculated. This is a key reason why both
175 the HiF and TPS methods result in a smaller bias for the IVLR than they do for the AVLR
176 (which is dependent upon the steepness of the entire slope for 20% to 80%) and the IP (which
177 is dependent upon the time of the IP).

The validation of the HiF and TPS surrogate methods in the situation where it would be used (e.g. in a trial with no discernible IP) is challenging. In such situations, the IP is absent, and therefore the criterion method cannot be used. We have therefore examined the criterion validity of this approach in runners with a discernible IP and this could be a limitation. In addition, we have examined the validity of this approach in rear-foot striking runners and as such, the outcomes from this study do not apply during forefoot running or to other populations e.g. other athletic groups or to other tasks e.g. walking.

To our knowledge this is the only published study to assess the validity of surrogate methods to determine IP indices, yet such methods are currently being used in the literature (Goss and Gross, 2013; Lieberman et al., 2010; Samaan et al., 2014). Good agreement of the HiF and TPS methods with the criterion method indicate both methods are likely to be valid surrogate approaches to estimate vGRF impact loading characteristics during rear-foot striking running. This, however, will be dependent upon the population studied. The smaller LOA and bias associated with the HiF method indicate that it should be used in preference to the TPS method when it is available.

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Figure captions

Figure 1: Example plots of the vGRF and their respective high (HiF) and low frequency (LoF) components for a rear-foot striker when running at 3.3 $m.s^{-1}$ on an instrumented treadmill. The figure highlights the three possible vGRF signal profiles: (A) an IP is easily identifiable; (B) an IP is not discernible and (C) where an IP does not exist. Note that in all cases a peak in the HiF signal still exists and is easily identifiable, but occurs earlier than the vGRF IP."

Figure 2: Bland-Altman plots for the right leg to assess agreement between the criterion measure and the HiF and TPS surrogate methods for the IP, AVLR and IVLR, respectively.