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Reliability of Loading Rate in Gait Analysis

V Abolins[1,2], K Nesenbergs[1] and E Bernans[2]

[1] Institute of Electronics and Computer Science, Riga, Latvia
[2] Latvian Academy of Sport Education, Riga, Latvia

valters.abolins@edi.lv

Abstract. Loading rate is an important parameter of running gait as it is commonly associated with increased risk of injury. In this paper we show, that most of the research related to calculating loading rate values from ground reaction force data cannot be directly compared, as the absolute loading rate values and the related first impact peak location and height are highly dependent on the filtering method used, cut-off frequency selected as well as loading rate calculation method selected. The results are based on running trial data from non-forefoot striking long distance runners gathered by the authors.

1. Introduction

Loading rate (LR) is an important parameter of running gait because it is commonly associated with increased risk of injury [1–3]. On the other hand, there is some contradicting research indicating no connection between LR and risk of injury [4,5]. In this paper, the authors show, that an important reason for these conflicting results could be the differing methodologies for calculating LR used in the research literature.

LR together with multiple other running gait parameters (e.g. stance time, first impact) is usually calculated from ground reaction force (GRF) data. GRF is a metric commonly used in running gait analysis, and can be used to acquire running gait parameters - either by itself or in conjunction with other data sources (e.g. torque can be calculated from GRF and video data). When talking about LR, usually only the vertical component of GRF (vGRF) is used, thus all further references to GRF in this article are assumed to be the vertical ground reaction force component only if not explicitly stated differently.

By definition the calculation of LR is simple - the maximum ground reaction force (F_{max}) reached by the foot during the first contact is divided by the time (T_{max}) to reach this force starting from the beginning of the impact. In practice, the calculation is more complex and has several sources of errors.

The first source of errors is finding the point in the impact phase, where the F_{max} is reached (as well as the corresponding time T_{max}). This point is usually referred to as the point of interest (POI). The GRF data of runners who are not forefoot strikers contains a distinct first spike with a maximum point called the first impact, which is used as POI for LR calculations. This first impact point is not found in the GRF data of forefoot strikers leading to multiple approached for calculating POI each potentially leading to different results. One approach to selecting POI in forefoot striker running GRF data is to find the first point where the slope of GRF curve changes [6,7]. Another approach used is to calculate the average POI of all non-forefoot strikers and use this value as POI for forefoot striker LR calculations [8]. This calculation method leads to varying results, as it is dependent on the specific experiment data, its acquisition, filtering methods, and other variables. For example, Liebermann et al. [8] calculate the average POI for non-forefoot strikers at 6.2% of stance time which can be used as

POI for forefoot strikers. Willy et al. calculate the same value as 13% [9] and Boyer et al. as 14% [10] while Goss and Gross settle on a range between 3% and 12% [11].
The second source of potential errors while calculating LR is the specific calculation method selected based on the identified POI. Because of mechanical and measurement noise as well as the shape of the impact curve the very beginning of the impact phase as well as close surroundings of POI are not regarded as good values for calculating LR. Common methods usually determine a starting (F_{start}) and ending (F_{end}) force for calculating the slope of LR, such that $0 < F_{start} < F_{end} < POI$. For example, $LR_{200N\text{-}90\%}$ is calculated as the slope of GRF starting from the point where it reaches the value of F_{start} = 200N, and ending at F_{end} = 90% of POI [8], while $LR_{20\%\text{-}80\%}$ is calculated as the GRF slope from F_{start} = 20% of POI till F_{end} = 80% of POI [12] (See figure 1).

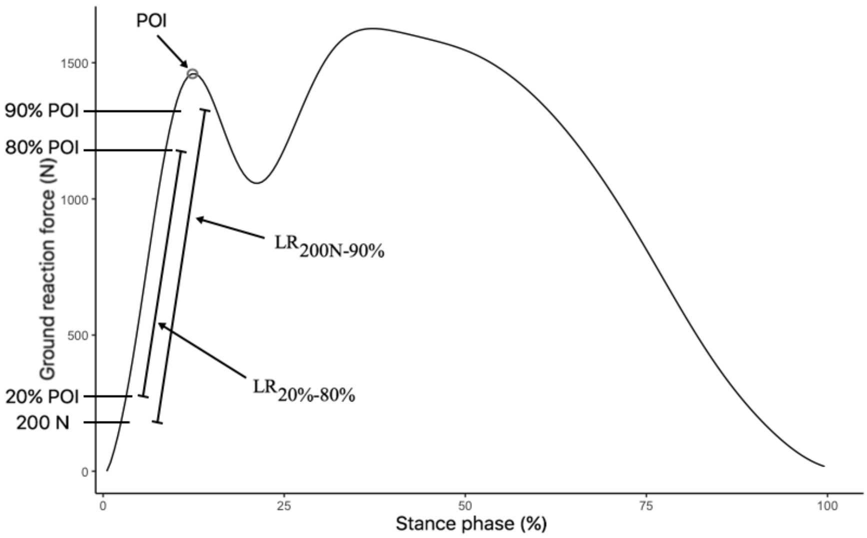

Figure 1. GRF curve example with POI and LR calculation ranges.

The third source of potential errors while calculating LR is the filtering method selected to process the GRF data before LR value is calculated. Even though there is no one filtering standard used for filtering running GRF data, a common choice is Butterworth low-pass filter, results of which depend on selected cut-off frequency. Researchers in their work use different cut-off frequencies, which can lead to different and incomparable results. Frequently used cut-off frequencies include 30 Hz [13–15], 50 Hz [16–18] and 100 Hz [19–21]. These frequencies are quite different and if used for pre-filtering the GRF can have a significant impact on the resulting LR. In this paper, we compare how calculated POI and resulting LR differ based on the choice of different filtering cut-off frequencies.

2. Methods

13 long distance non-forefoot strike runners (all male) participated in this study. The mean values ± SD of the key physical characteristics of the group are as follows: age = 26.85 ± 4.78 years, height = 180.54 ± 8.66 cm, weight = 69.92 ± 8.28 kg, time to run 21km = 72.5 ± 7.5 min. All participants were injury free 6 months prior to the experiment.
Running trials were conducted on a 30 m wooden track. GRF data was collected using two 600 mm x 400 mm force platforms (*BTS P-6000*, Italy), sampled at 1000 Hz. To control running speed, 3 photocells (*Microgate Polifemo Light Radio*, Italy) were used.
Running speed was set between 18 km/h and 19 km/h. Participants had time to practice and get used to this speed and running conditions. They could start the trials whenever they felt they are ready. They were asked to run in their preferred running shoes and not to try to hit the force platforms.
All participants completed 3 clean over ground running trials. During runs, GRF from force plates was measured. If there was no visual evidence of missing the force platforms and the speed was within 18-19 km/h range, the trial was accepted. Data of both feet stances was collected.

The trial for each participant which had the speed closest to 19 km/h was selected for further analysis. Both feet stances were analysed. GRF data was normalized in Body weight (BW) and was filtered using a low-pass fourth-order Butterworth filter with cut-off frequencies of 30 Hz, 50 Hz, and 100 Hz. POI, $LR_{200N\text{-}90\%}$ and $LR_{20\%\text{-}80\%}$ values were calculated from all filtered data. The stance phase was defined between ground contact (vGRF > 20 N) and take-off (vGRF < 20 N) [22].
Pearson's correlation coefficient was calculated for the POI, $LR_{200N\text{-}90\%}$ and $LR_{20\%\text{-}80\%}$ between each pair of cut-off frequencies. The significance of mean differences was calculated using Student's t-test with paired samples. All calculation was made in *R version 3.4.3.* [23].

3. Results

The mean POI was 16.87% (30 Hz), 13.39% (50Hz) and 11.54% (100Hz) for the respective cut-off frequencies. The POI position was decreasing when choosing higher cut-off frequency while resulting $LR_{200N\text{-}90\%}$ and $LR_{20\%\text{-}80\%}$ was increasing with higher cut-off frequencies (see table 1).

Table 1. LR and POI results with different cut-off frequencies.

	30 Hz *Mean (SD)*	50 Hz *Mean (SD)*	100 Hz *Mean (SD)*
POI (%)	16.87 (6.01)	13.39 (3.49)	11.54 (3.65)
$LR_{200N\text{-}90\%}$ (BW/s)	119.18 (21.76)	166.27 (50.52)	200.11 (63.73)
$LR_{20\%\text{-}80\%}$ (BW/s)	129.35 (22.45)	181.01 (56.64)	230.00 (77.74)

A significant difference in POI and both LR variation values between all three cut-off frequency combinations (see table 2) was observed. With higher cut-off frequency LR was higher.

Table 2. Differences of LR and POI results between pairs of cut-off frequencies.

		Mean	*95% CI*	*p-value*
30 Hz vs 50 Hz	**POI (%)**	3.48	(1.37, 5.58)	0.002
	$LR_{200N\text{-}90\%}$ (BW/s)	-47.09	(-59.62, 5.58)	< 0.001
	$LR_{20\%\text{-}80\%}$ (BW/s)	-51.66	(-66.20, -37.12)	< 0.001
30 Hz vs 100 Hz	**POI (%)**	5.33	(2.58, 8.08)	<0.001
	$LR_{200N\text{-}90\%}$ (BW/s)	-80.94	(-100.00, -61.87)	< 0.001
	$LR_{20\%\text{-}80\%}$ (BW/s)	-100.66	(-124.80, -76.51)	< 0.001
50 Hz vs 100 Hz	**POI (%)**	1.85	(0.05, 3.65)	0.045
	$LR_{200N\text{-}90\%}$ (BW/s)	-33.85	(-46.87, -20.82)	< 0.001
	$LR_{20\%\text{-}80\%}$ (BW/s)	-48.99	(-63.74, -34.25)	< 0.001

There was also a significant difference between $LR_{200N\text{-}90\%}$ and $LR_{20\%\text{-}80\%}$ when choosing different cut-off frequencies. When GRF was filtered with 30 Hz cut-off frequency mean difference between $LR_{200N\text{-}90\%}$ and $LR_{20\%\text{-}80\%}$ was -10.17 BW/s ($p < 0.001$), but when GRF was filtered with 50 and 100 Hz frequencies, the same difference was -14.72 BW/s ($p < 0.001$) and -29.89 BW/s ($p < 0.001$) respectively. $LR_{200N\text{-}90\%}$ was always lower than $LR_{20\%\text{-}80\%}$ (see table 3).

Table 3. Differences and correlation between two types of LR results at different cut-off frequencies.

	30 Hz	50 Hz	100 Hz
Mean difference (BW/s)	-10.17	-14.74	-29.89
95% CI	(-11.19, -9.15)	(-17.52, -11.97)	(-39.57, -20.20)
r (correlation coefficient)	0.994	0.998	0.962
95% CI	(0.986, 0.997)	(0.996, 0.999)	(0.915, 0.983)

There was a significant correlation in both loading rates between all 3 cut-off frequencies (Table 4). There was a significant correlation in POI between 30 Hz vs. 50 Hz cut-off frequencies, but there was no correlation between 30 Hz vs. 100 Hz and 50 Hz vs. 100 Hz cut-off frequencies (Table 4).

Table 4. Correlation of LR and POI results between pairs of cut-off frequencies.

		r (correlation c.)	*95% CI*	*p-value*
30 Hz vs 50 Hz	**POI**	0.505	(0.146, 0.746)	0.009
	$LR_{200N-90\%}$	0.941	(0.872, 0.974)	< 0.001
	$LR_{20\%-80\%}$	0.950	(0.891, 0.978)	< 0.001
30 Hz vs 100 Hz	**POI**	0.069	(-0.327, 0.444)	0.738
	$LR_{200N-90\%}$	0.832	(0.656, 0.922)	< 0.001
	$LR_{20\%-80\%}$	0.852	(0.693, 0.932)	< 0.001
50 Hz vs 100 Hz	**POI**	0.220	(-0.183, 0.560)	0.280
	$LR_{200N-90\%}$	0.865	(0.719, 0.938)	< 0.001
	$LR_{20\%-80\%}$	0.899	(0.786, 0.954)	< 0.001

4. Discussion

With a relative increase in the cut-off frequency used, the POI is reduced moving towards the beginning of the impact phase, while the calculated LR is increasing. In addition to the reduction of POI time, it has been noted by Kiernan et al., that force of the first impact (at POI) is increased if the cut-off frequency is increased [24]. Both of these factors contribute to the increase of LR, as it is a division of the force vs time at POI. Even though previous research states that average POI is located at fixed points our results show, that it is dependent on the cut-off frequency selected. For example, Lieberman et al. did not filter GRF data and arrived at 6.2% POI [8], while Willy et al. and Boyer et al. used Butterworth low-pass filter with 50Hz cut-off frequency arriving at respective POI values of 13% [9] and 14% [10]. The results acquired by the authors confirm this, showing that higher cut-off frequency leads to lower POI values and provides a similar 13.39% POI value at 50Hz cut-off frequency. The differences between both types of LR calculations are explained by the fact, that GRF data growth rate decreases as it approaches the POI, where growth rate is 0. Thus $LR_{200N-90\%}$ is lower than $LR_{20\%-80\%}$, because it covers 10% more of the GRF data, with a lower growth rate (see figure 2), leading to another reason why results of both of these methods cannot be directly compared in different research.

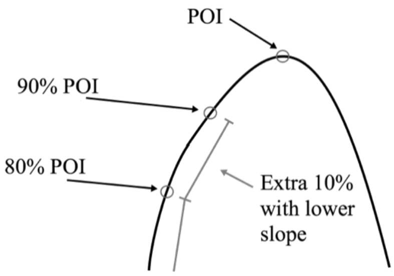

Figure 2. Locations of 80%, 90% and 100% POI on GRF curve.

For a specific case, even though absolute difference increases with the increased cut-off frequency it is not important which specific method of calculation is chosen, as they have high correlation and the ranging is preserved. The same relative ranging property is also preserved while one LR calculation method is used with different cut-off frequencies even though absolute values change.

This means, that for a specific case the choice of filtering cut-off frequency does not matter, as the relative comparison of LR values will hold, but POI and LR values cannot be compared with the work of other authors if their selected cut-off frequencies and trial running speeds are different, as the first impact peak dependence on the cut-off frequency also changes with running speed [24].

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