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A Metric for Identifying Stress Fractures in Runners

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Abstract—

Purpose: **Stress fractures are common overuse running injuries. Individuals with stress fractures exhibit running biomechanics characterized by elevated impact peak and loading rate. While elevated impact peak and loading rate are associated with stress fractures, there are few established metrics used to identify the presence of stress fractures in individuals. Here this study aims to exploit the linear relationship between the impact peak and loading rate to establish a metric to help identify individuals with stress fractures. We hypothesize that the ratio between the impact peak and loading rate will serve as a metric to delineate between healthy controls and those with stress fractures.**

Methods: **Fifteen healthy controls and 11 individuals with stress fractures performed a running protocol. A linear regression model fit to the stress fracture impact peak and loading rate data produced a lower 95% confidence limit boundary that served as the demarcation line between the two groups.**

Results: **Individuals with stress fractures tended to reside above the line with the line accurately classifying 82% of the individuals with stress fractures.**

Conclusion: **The analysis supported the hypothesis and demonstrated how the relationship between impact peak and loading rate can help identify the presence of stress fractures in individuals.**

Clinical Relevance— **The relationship between impact peak and loading rate has the potential to serve as clinically useful metric to identify stress fractures during running.**

I. INTRODUCTION

Approximately 50% of all running injuries are attributed to stress fractures [1-4]. Individuals suffering from stress fractures are characterized as having elevated impact peaks and loading rates during running [4-6]. These changes in running biomechanics can represent an inability to attenuate shock that can contribute to the development of stress fractures [4]. While greater impact peaks and loading rates are often associated with stress fractures, it has yet to be established what values of impact peaks and/or loading rates are indicative of injury. Studies have investigated the correlative relationships of impact peaks and loading rates to tibial stresses and accelerations in individuals with stress fractures [7-9]. While moderate correlations were observed, additional studies have shown that the linear relationship between variables, such as, peak force and loading rate, may provide a better metric to denote injurious biomechanics [10,11]. Therefore, the objective of this study was to investigate the relationship between impact peak and loading rate to determine a quantitative metric to differentiate between controls and those suffering from stress fractures.

Stress fractures arise due to a combination of biomechanical changes in limb loading dynamics during tasks like running [4-6,12,13]. Despite the combined effect these biomechanical changes have on limb loading, features such as impact peaks and loading rates are often analyzed independently. However, Alzakerin et al. (2020) demonstrated that the relationship between peak vertical ground reaction force and loading rate could be exploited to differentiate between healthy and pathological movement [14]. The study revealed that there is a strong linear relationship between peak force and loading rate in healthy controls, that is not present in individuals with injurious biomechanics as individuals with altered biomechanics present with variable peak force to loading rate ratios. The results of this work are significant because it provides a quantifiable and graphical metric to differentiate between healthy and pathological movement. Given that individuals suffering from stress fractures also exhibit altered peak force and loading rate dynamics, it is believed that the individuals with stress fractures will exhibit greater loading rate to impact peak ratio than the healthy controls [4,6]. Furthermore, the resulting loading rate to impact peak ratio could provide a metric to delineate between the controls and stress fracture individuals. The development of a metric derived from the impact peak and loading rate to detect stress fractures could have a significant impact on the early identification of stress fractures and aid in reducing the high incidences of stress fractures in runners.

The objective of this study was to identify a new metric to detect the presence of stress fractures in elite runners. To accomplish this objective, we investigated the linear relationship between impact peak and loading rate between the healthy controls and stress fracture individuals. Then we

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evaluated the ability of the loading rate to impact peak relationship to delineate between healthy controls and those suffering from stress fractures. We hypothesized that the linear relationship between impact peak and loading rate in individuals with stress fracture group would help to accurately differentiate between runners with and without stress fractures. The ability to delineate between runners with and without stress fractures based on the linear relationship between impact peak and loading rate could provide an additional metric to aid in the early detection of stress fractures in individuals.

II. METHODS

A. *Instrumented Gait Analysis*

Fifteen controls (age 19.1 ± 0.8 yrs; height 1.8 ± 0.1 m; mass 64.7 ± 8.7 kg; miles per week 58.4 ± 19.3 miles) and 11 individuals with history of stress fractures (age 19.4 ± 0.8 yrs; height 1.8 ± 0.1 m; mass 63.7 ± 6.9 kg; miles per week 58.6 ± 16.9 miles) participated in a running protocol. Each participant provided written consent to participate in the study in accordance with the institutional review board. Participants ran on an instrumented split-belt treadmill (Bertec Corporation, Columbus, Ohio). Participants started with a two-minute warm-up period where they ran at 2.5 m/s followed by running at 3.3m/s for 30 seconds. Running variables were then extracted from the vertical ground reaction force (vGRF) data that was collected at 1200 Hz and low-pass filtered at 35 Hz using a 4th order Butterworth filter. All the running data was extracted when the individuals were running at 3.3 m/s. All participants used for this study exhibited a rearfoot striking running pattern. Participants with history of stress fractures had mixed stress fracture types, including tibial, fibular, and metatarsal stress fractures.

B. *Feature Extraction*

The variables of interest were impact peak, loading rate and loading rate to impact peak ratio that were obtained during the 3.3 m/s running trial. The impact peak is the first vGRF peak during each stride. The loading rate is the slope between 20 and 80% of the vGRF data between foot strike and impact peak. Both impact peak and loading rate were normalized to individuals body weight (BW). The ratio was created by dividing the loading rate by the impact peak. These variables of interest were extracted using a custom MATLAB code (MATLAB R2019b, TheMathWorks, Inc., Natick, MA).

C. *Classification and Regression Analysis*

Scatterplots of the impact peak versus loading rate data suggested that there was a linear relationship between the two variables in the stress fracture group. A linear regression model was fit to the stress fracture group data. Analyses were conducted that evaluated the statistical significance of the model coefficients and generated the 95% upper and lower confidence limits for the predicted line. The lower 95% confidence limit for the predicted line was used to define the region of healthy running dynamics as the region below the 95% lower confidence limit.

Each variable of interest was tested as the predictor using a Linear Support Vector Machine (SVM) algorithm to classify between the two groups. The analysis used 80% of the data for the training set and 20% as the test set and the Linear SVM algorithm was applied to both sets of data. The performances of the variables were compared based on the model accuracy, sensitivity and specificity.

D. *Statistical Analysis*

A t-test was conducted to assess differences in mean age, height, mass, running speed, impact peak, loading rate and loading rate to impact peak ratio between the control and stress fracture groups (α=0.05). All the statistical analyses were conducted in MINITAB (MINITAB, Version 18, State College, PA, USA).

III. RESULTS

There were no significant differences in mean age, height, mass, and miles run per week between the control and stress fracture groups at the 5% significance level (Table 1). Both loading rate and the loading rate to impact peak ratio were significantly greater in the stress fracture individuals than controls ($p<0.01$; $p<0.01$) (Table 2). No significant difference was found in impact peak ($p=0.68$) (Table 2).

Table 1. Comparison of age, height, mass, and miles run per week between the control and stress fracture individuals.

Variable	Controls	Stress Fracture	P-Value
Age (years)	19.1 ± 0.8	19.4 ± 0.8	0.35
Height (m)	1.8 ± 0.1	1.8 ± 0.1	0.73
Mass (kg)	64.7 ± 8.7	63.7 ± 6.9	0.84
Miles per Week (miles)	58.4 ± 19.3	58.6 ± 16.9	0.97

Table 2. Comparison of impact peak, loading rate and loading rate to impact peak ratio between the control and stress fracture individuals.

Variable	Controls	Stress Fracture	P-Value
Impact Peak (BW)	1.6 ± 0.2	1.6 ± 0.2	0.68
Loading Rate (BW/s)	45.8 ± 17.6	61.4 ± 16.4	0.002
Loading Rate to Impact Peak Ratio (1/s)	28.5 ± 10.2	38.5 ± 7.1	<0.001

A fitted linear regression model was generated for the stress fracture data (Eq. 1) and the 95% lower confidence limit served as the line to demarcate between the healthy and stress fracture regions (Table 3). The appropriateness of the linear regression model was validated by the evaluation of the residuals. A plot of the model residuals indicated that they were normally distributed and the Anderson-Darling test for normality of the model residuals was performed and confirmed that the data followed a normal distribution. The results of both analyses supported the appropriateness of the linear regression model selection.

$$\text{Loading Rate} = (60.6 * \text{Impact Peak}) - 34.3 \quad \text{(Eq. 1)}$$

Table 3. Linear regression equation coefficients and model statistics. (R^2=0.65)

Term	Coefficient	95% CI
Intercept	-34.4	(-67.0, -1.5)
Slope	60.6	(40.0, 81.2)

The assessment of the relationship and associated classification line successfully placed 82% of the stress fracture individuals in the injured region (Fig. 1). The model appropriately placed 77% of the controls in the healthy region. The results indicate that the ratio of loading rate to impact peak is an impactful classification feature.

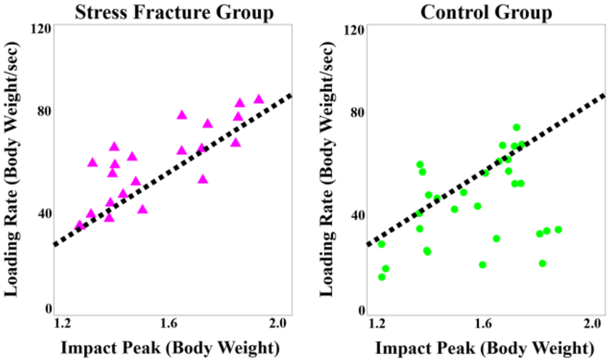

Figure 1: The loading rate plotted against the impact peak for the stress fracture group and control group. The line represents the upper 99% confidence limit for a linear regression of the control data.

The loading rate to impact peak ratio Linear SVM model outperformed the Linear SVM models based on the impact peak and loading rate alone. Additionally, the results of the Linear SVM supported the linear regression analysis results as they produced similar lines of demarcation between the two groups. The overall model accuracy, sensitivity and specificity for the loading rate to impact peak ratio were 75%, 64%, and 77%, respectively. Comparatively, the model accuracy, sensitivity, and specificity for the impact peak were 58%, 50%, and 63%, and for the loading rate the accuracy, sensitivity, and specificity were 65%, 59%, and 70%.

IV. DISCUSSION

The objectives of this study were to investigate the relationship between impact peak and loading rate in healthy controls and stress fracture individuals and evaluate the ability of this ratio to classify between healthy controls and individuals with stress fractures. It was hypothesized that this loading rate to impact peak ratio would accurately classify individuals into the healthy controls and stress fracture groups. The results supported the hypothesis as the loading rate to impact peak ratio was significantly greater in the stress fracture individuals than the healthy controls. The loading rate to impact peak also served as a strong classifier as it accurately classified 82% individuals into the stress fracture group. The performance of the loading rate to impact peak ratio is consistent with previous studies that yielded similar accuracy when classifying individuals with stress fractures using kinematic and kinetic features collected during running [6]. While classification accuracy here could be increased with the inclusion of additional metrics, the significance of this work is the identification of a new clinically relevant metric to help classify individuals with stress fractures from running biomechanics. Moreover, an advantage of this metric is that beyond providing a quantitative value, the visual relationship between the impact peak and loading rate also serves as a way to track individuals movement toward or away from this dividing line which can be indicative of their risk or diminished risk of stress fractures. Thus, there is a valuable clinical application for this work.

Impact peak and loading rate data are representative of the forces exerted and the rate the forces are exerted on the limb during dynamic tasks [6,13,15,16]. Thus, the evaluation of these metrics together, as represented by the loading rate to impact peak ratio, may be representative of limb loading dynamics. Therefore, the elevated loading rate to impact peak ratio observed in individuals with stress fractures may be representative of the limb functioning outside of its dynamic operating range. This idea is supported by the fact that the majority of the healthy controls resided below the stress fracture individuals based on the linear dividing line. While the line was used to delineate between alternate limb loading dynamics between the controls and stress fracture individuals, it may be possible that this linear relationship could be employed to aid in the delineation and/or identification of other musculoskeletal conditions. While additional research is needed to support this theory, the results of this study indicated that the impact peak versus loading rate relationship could be clinically useful in the identification of running biomechanics associated with stress fractures.

The often binary output of movement classification models as either healthy or injured make these models ideal for the identification and classification of musculoskeletal conditions and/or injuries [5,6,14,17,18]. However, alternate metrics or approaches may be needed to monitor injury or rehabilitation progression. An advantage of the loading rate to impact peak ratio is that the dividing line serves as a clear visual distinction and cut-off criteria that can function to both delineate between healthy and injured groups but also help in tracking changes in limb loading dynamics. After the identification of an injury such as stress fractures, rehabilitation protocols function to restore healthy motor control. The ability to track changes in limb loading dynamics can transform and expand the role of the loading rate to impact peak ratio metric beyond that of a classification metric to that of a monitoring and assessment metric. While additional work is needed to establish this ratio as an assessment metric, its potential as an assessment metric is promising.

A limitation of this study is that footwear type was not standardized across the participants. Therefore, it is possible that differences in running biomechanics could be attributed to differences in footwear. However, given that the objective of this work was to evaluate the force and loading rate dynamics during running that are associated with stress fractures, allowing the participants to run in their preferred footwear better ensured that they produced the same running biomechanics during the study as they produce during their training. This is supported by the fact that multiple participants that resided in the region associated with stress fractures were evaluated prospectively and went on to develop stress fractures after participating in the study. Thus, despite not suffering from stress fractures at the time of the study, the running biomechanics they produced during the study were found to be associated with this injury.

V. CONCLUSION

The study was able to employ the relationship between impact peak and loading rate to aid in the classification of individuals with stress fractures. Since the loading rate to impact peak ratio was able to accurately classify 82% of the stress fracture individuals, it has the potential to serve as a valuable metric for the identification of stress fractures in runners. The loading rate to impact peak ratio is a robust metric as it was able to identify running biomechanics associated with stress fractures prior to the individuals developing a stress fracture. This study used the relationship between established metrics that are associated with injurious biomechanics to delineate between heathy controls and individuals with stress fractures and thus identifying an additional metric to aid in injury biomechanics classification.

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