EXAMINING THE EFFECTS OF CLEAT STIFFNESS ON SPEED AND FORCE

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ABSTRACT

Performance in high-impact explosive sports (e.g. American football, soccer, lacrosse) requires traction from spiked athletic shoes, known as cleats. The behavior of cleats in aiding speed generation is unknown, especially as their stiff plastic soles become more pliable. To quantify the effect cleat deterioration has on speed and to understand the force involved in the ground-foot interactions, peak force and acceleration were measured while running with a new and old pair of New Balance Freeze LX cleats. Force was measured on the ball of the foot with an accelerometer on the top of the shoe above the toes. Bending stiffness values were measured by displacement due to an applied force. The average peak force values suggested a significant difference as new cleats exhibited a higher peak force at all speeds; however, the old pair of cleats produced 13% greater jerk at lower speeds and similar high-speed jerk values.

INTRODUCTION

Cleats and similar athletic footwear are a crucial component of explosive sports although there are no regulations for parameters such as sole stiffness, weight, and spike pattern [1]. Substantial evidence exists proving bending stiffness of shoe soles helps reduce the amount of energy lost in joints while jumping, improving overall performance for jumping-related athletic movements [2]. While this may apply very well to basketball or high jump in track and field, the knowledge does not transfer to an analysis on athletic shoe stiffness and its effect on speed, especially as athletic footwear ages and degrades. Thus, manufacturers don't entirely know how to optimize speed and mitigate injuries in designing cleat soles and stiffnesses.

In 2015, Crandall et al. first quantified the forefoot bending stiffness of American football shoes of different spike patterns and styles, contributing a greater understanding of the foot's kinematics and a comparison of cleats from different manufacturers [3]. However, this research serves to compare a variety of new cleats and doesn't provide information on how their soles wear out. Consequently, it is unknown if a reduction in bending stiffness due to deteriorating footwear may affect speed or if it could affect impact forces while running on artificial turf, an indicator of potential for injury. Thus, more light can be shed on this degradation and the effect it has on sports performance through observation of the peak normal force as the foot strikes the ground and the foot's jerk while running in a straight line at various constant speeds. Analyzing jerk illustrates how fast the foot is accelerating after striking the ground and analyzing peak forces provides insight into the magnitude of force acting on joints and leg muscles while running.

Two separate pairs New Balance Freeze LX cleats– one new and one worn in over the course of two years – were tested to determine if stiffer soles affect jerk and with what force requirement. A force sensor and accelerometer were strapped to one foot before running in a straight line at a constant speed determined by a steps-per-minute cadence. Force and acceleration data provided insight on average peak forces while running and jerk as the foot pushes off the ground. To establish the basis of comparison, the bending stiffnesses of both cleats were calculated by their measured angular displacement in response to an applied force.

Obtaining locomotive data at various constant speeds would allow for the development of jerk-force and jerk-speed relationships, shedding light on any statistically significant behavioral differences in the cleats. Quantifying cleat deterioration can encourage further focus on bending stiffness as a design parameter aiding speed and preventing injury while also determining whether it is necessary to make personal economic decisions to purchase new footwear or rely on broken-in pairs.

BACKGROUND

RUNNING: FOOT INTERACTION WITH THE GROUND

Stress and force exerted and absorbed by the foot while running can be a complex combination of running mechanics, weight of the runner, pronation, ligament flexibility, etc,; however, in the context of this study it is best to take an orthogonal look at the foot as it strikes the ground to understand the major angles and forces associated with running at various speeds with football cleats. In Figure 1, a side profile of the foot in stride is shown to highlight major forces and geometric properties.

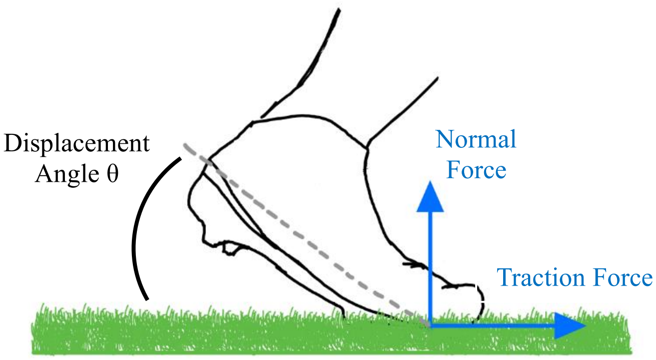


Figure 1: In forward motion, the foot strikes the ground and creates the angle shown above. The spike pattern grips artificial turf or grass, allowing for stability when performing high-speed linear movements or lateral cuts. The weight and acceleration of the runner transfers to a normal force while the forward momentum and grip of the spikes causes a forward traction force.

As the foot strikes the ground, the mass of the body running as well as the downward acceleration creates a large normal force while the spike pattern of the cleats grips the surface and causes a traction force to help propel the foot forward as the runner continues their forward momentum. The angle that the foot creates with the ground results in a bending of the cleat sole, causing a resultant moment from the cleat dependent on the stiffness of the sole. Force transmission to the ground can be viewed as a good indicator of speed and impact forces, thus, an understanding of the normal force in the ground and foot interaction is critical to this study [4].

AMERICAN FOOTBALL CLEAT STIFFNESS

Just like rotational springs, shoe soles store energy and apply resultant torques in response to displacement. A 2015 study concluded that for 21 different size 12 American football cleat models of differing manufacturers and shoe types, stiffness values fell in a range of 0.10-0.35 Nm/deg, with peak stiffness values happening in a range of 65-70 degrees of flexion – motion pictured in Figure 2 [1]. To obtain more reliable results, the Football American Shoe Tester (FAST) was developed and in a subsequent 2016 study, the same group found stiffness values for 30 pairs of American football cleats to fall in the 0.27-0.8 Nm/deg range with peak torque ranging from 11.8-25.5 Nm [5]. Prior research supports the belief that athletic shoes are a significant factor in reducing the frequency or severity of 1 MTP (shown in Figure 2) injuries, known as turf toe, although there is no focus placed on the age and condition of footwear and what an optimal bending stiffness value may be for injury prevention.

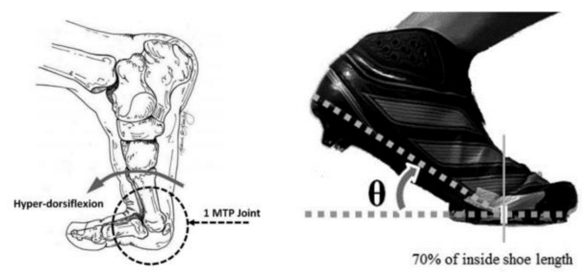


Figure 2: In forward motion, the foot strikes the ground and creates the angle shown above [1]. The spike pattern grips artificial turf or grass, allowing for stability when performing high-speed linear movements or lateral cuts. The majority of bending and stress is placed on the 1 MTP joint also shown [1].

As there are currently no standards for bending stiffness of American football athletic shoes, and important prior research finds itself more focused on injury prevention, it is unknown if the bending stiffness of footwear could have a significant effect acceleration and speed [2]. Research done by Stefanyshyn and Nigg has supported the notion that greater stiffness values limit energy lost in jumping motions; however, no change in energy generation was discovered in running tests although energy absorbed was decreased [6]. Running involves maintaining forward momentum and a greater frequency of foot falls in comparison to jumping and thus the motion may engage in a more complicated relationship with shoe stiffness. Still, it is unknown if there is a substantial added benefit in having stiff shoes or cleats while running and, thus, this proposed comparison between a new pair of cleats and an older pair serves to quantify a difference in jerk provided during the foot's interaction with the ground.

MECHANICS OF AMERICAN FOOTBALL CLEATS AND SURFACE INTERACTIONS

When evaluating performance, especially considering the inherent lack of guidelines and regulations for design parameters in athletic footwear, the mechanical interaction between the foot, cleat, and playing surface reveals interesting information in the context of this study. Kent et al. in 2015 determined that artificial surfaces do not exhibit similar injury mitigating properties as natural grass, particularly in allowing the foot to move over its full range of motion and allowing for slippage to limit force exerted on lower limbs [1, 6]. Considering the popularity of artificial turf in sports such as football, soccer, and lacrosse, this lack of injury mitigating properties could cause a noticeable difference in injury frequency. Furthermore, Kent describes that choice of cleat thus becomes critically important on artificial surfaces since force limiting factors are constrained to cleat pattern [1]. Additionally, it can be hypothesized that bending stiffness of the shoe sole could have an effect of load distribution when translating or rotating the foot on an artificial surface, pointing to stiffness as a possible design parameter which, in the context of this study, would purposefully target optimization of forward acceleration but also injury prevention.

EXPERIMENTAL DESIGN

CLEAT STIFFNESS MEASUREMENT

To determine a baseline for the comparison of the old and new pairs of New Balance Freeze LX Cleats, reactions to a hanging weight were measured to observe a difference in their bending stiffnesses, a design parameter with no requirements in cleat manufacturing. To successfully measure this difference, both cleats were held in a vice, keeping the heel still while the toe would bend as a 1.5 kg weight hanging approximately 55.51 ± 0.56 mm from the vice in the new cleat and 52.51 ± 0.35 mm for the old cleat caused a displacement. The setup is displayed in Figure 3.

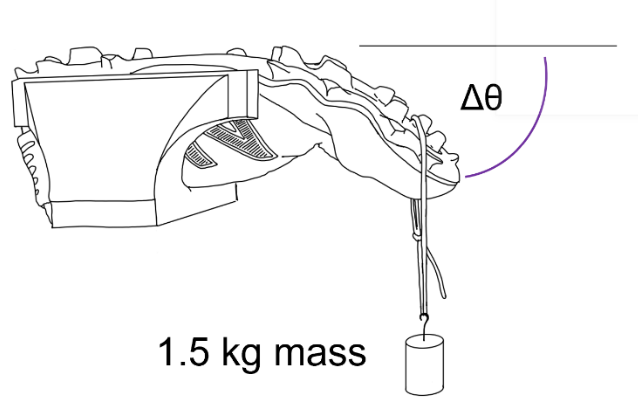


Figure 3: Cleat is placed in a vice as a 1.5kg weight is hung from the spikes to cause a displacement angle.

Pictures were taken next to a scale oriented along the axis of the sole to approximate a linear displacement rather than a rotational one. The scale was clamped to another workbench to keep it still while the cleat moved in response to a 1.5 kg hanging mass. Pictures were placed into SolidWorks to use reference points to determine an angular displacement.

RUNNING TESTS

To compare the cleats and any added benefit to speed generation, both were fitted with a Vernier 3-Axis Accelerometer (3D) to measure acceleration in m/s^2 while an Interlink Electronics FSR 406 (IL-406) was taped to the runner's foot and used to measure a raw voltage (V) output in response to force. The IL-406 was calibrated with a Vernier Force Plate (FP) which measures force in N. The experimental setup is shown in Figure 4.

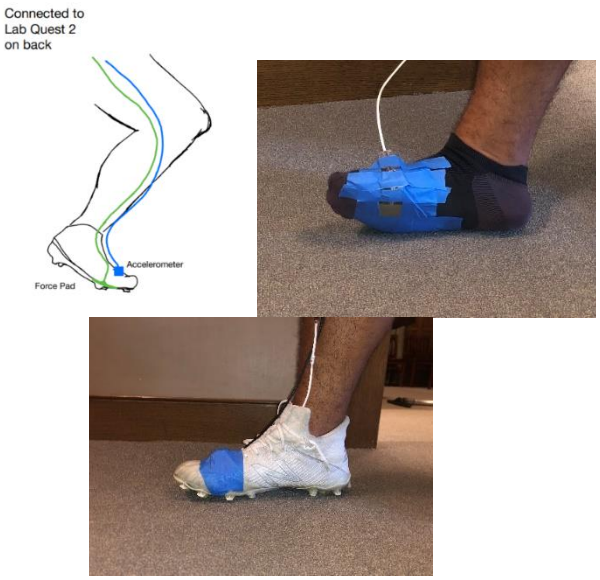
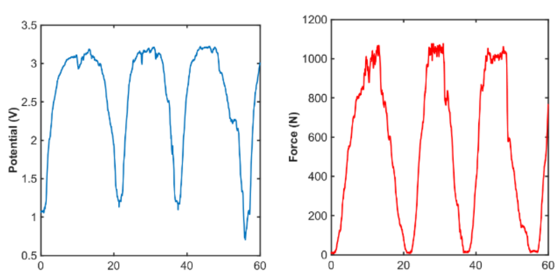
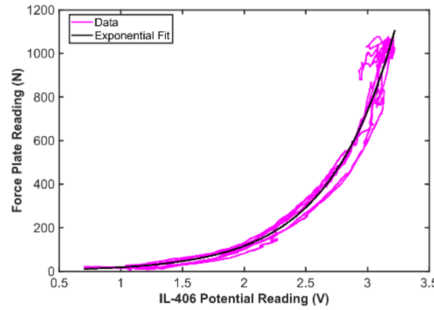


Figure 4: Experimental setup showing use of an Interlink Electronics FSR 406 (IL-406), measuring raw potential (0-5V), and a Vernier 3-Axis Accelerometer (3D) on the toe measuring downward and forward acceleration of the foot in m/s^2. The physical setup is also shown, with the force pad taped to the runner's sock and the accelerometer taped to the top of the cleat. Both cables were taped to the runner's leg and connected to a LabQuest2 in a backpack.

To obtain a reading of the force between the foot and the ground during each run, the voltage output of the Interlink Electronics FSR 406 (IL-406) was calibrated with the Vernier Force Plate (FP). With a slow step and increase in weight applied on the force plate through the foot and force sensitive resistor, force and potential readings were obtained and plotted against each other to illustrate a relationship. Figure 5 shows the raw data from one such calibration.



(a) (b)



(c)

Figure 5: The Potential v. Time graph is shown in (a) while the Force v. Time reading is shown in (b). The subsequent graph (c) shows Force v. Potential to determine an exponential fit that is used to calculate force from potential while running. Data was recorded at a sampling rate of 500 Hz over the course of one minute to allow for three relatively smooth increases and decreases in force applied to the plate through the force pad.

The new pair was tested first, with data recorded at various speeds determined by running cadence. Three runs were performed at each step cadence: 150 BPM, 160 BPM, 170 BPM, and 200 BPM. Steps were matched to a metronome playing during the 10 second run on turf. The exact same procedure was applied while testing the old cleats afterward. Once the force pad was secured to the runner's sock, the cleat was put on and the accelerometer was strapped to the top of the foot near the beginning of the laces as shown in Figure 4. All data was acquired at a sampling rate of 500 Hz through a Vernier LabQuest2.

RESULTS AND DISCUSSION

STIFFNESS VALUES

To quantify the bending stiffness of both cleats the pictures of both cleats pre and post displacement were converted to SolidWorks sketches to use reference points and obtain a displacement value. The sketches for both the old and new pair of cleats are shown below in Figure 6.

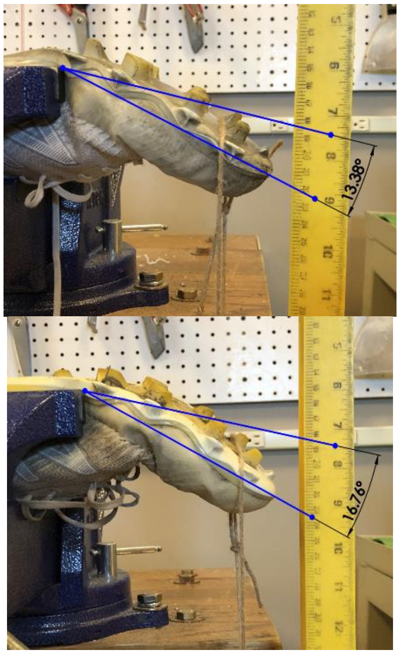


Figure 6: New cleats are shown on the top and the old pair are shown on the bottom. Angle references and lines are created in SolidWorks to measure the angle with Smart Dimension software. The new cleats show a displacement angle of 13.38˚ while the old cleats displaced 16.76˚. The same weight was placed on the cleats around the same portion of the spikes.

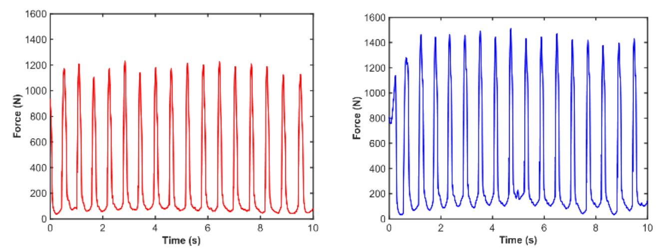
The reference point for both angles was dependent on the cleat's natural bent angle before any load is applied. This point was referenced from the corner of the vice (the estimated pivot point) and stretches to the scale point where the cleat originally touched. In their displaced states, a line was drawn from the same pivot point through the same tip of the toe box to see how the axis line of the cleat's sole shifted in response to the weight. Smart Dimension in SolidWorks was then used to calculate the angle between these two lines, a value which was then used to calculate the bending stiffness of both cleats according to Eq. 1 where M is the applied moment.

$$K = \frac{M}{\Delta\theta} \qquad (1)$$

The bending stiffness for the new pair of cleats was calculated to be 0.05773 ± 0.00061 Nm/deg while the old pair of cleats exhibited a bending stiffness of 0.04610 ± 0.00031 Nm/deg. These values are much smaller than the stiffness values calculated in prior research, most likely due to the small forces involved in this measurement resulting in a tiny flexion angle of the sole. Although, according to this measurement, the new cleats are about 25% stiffer than the old cleats, a difference attributed to consistent use and bending of the old cleat sole while playing American Football. This reduction in stiffness creates a more pliable shoe that more easily follows the motion of the foot rather than maintaining its stiff position, a phenomenon that is hypothesized in this research to affect speed generation and force while running.

FORCE MEASUREMENTS

Calibration relationships allowed for determination of force on the foot throughout each run, with separate calibrations performed any time a cleat was to be placed on the foot. Subsequent graphs of Force v. Time for running tests allowed for peak force in each footfall to be located to obtain an average peak force as the foot strikes the ground for the new and old cleats. An example of a Force v. Time graph while running is shown in Figure 7.



(a) (b)

Figure 7: Two sets of Force v. Time running data are shown corresponding to a 200 BPM running cadence. Graph (a) represents the old pair of cleats while (b) represents the new pair. The absolute maximum force reading in every footfall >2s was determined, providing a buffer time to allow for acceleration to the specific running cadence.

Runs with the old cleats were all characterized by lower peak forces in footfall when compared to the new cleats. Each peak force of the footfalls were located and the mean, standard deviation, and 95% confidence uncertainty were determined for each cadence with the old and new cleats. These values were graphed to display trends as cadence increases but also portray differences in the force experienced while wearing the new and old pair of cleats. Figure 8 illustrates these trends.

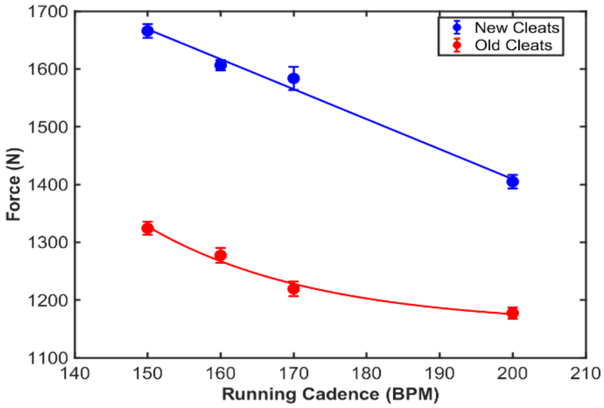


Figure 8: Average peak normal force while running for each cadence. The new cleats are fit with the line $F_{new} = (-5.194 \pm 0.359 \frac{N}{BPM})x + (2448 \pm 62\ N)$ while the old cleats are fit by a decreasing exponential $F_{old} = \left(171 \pm 24 \frac{N}{BPM}\right) e^{(-0.043 \pm 0.015)*(x-150)} + (1156 \pm 25\ N)$

Both cleats exhibit a trend of decreasing peak force as speed increases; however, the newer cleats exhibit this trend at higher overall forces represented by a line while the old cleats are better represented with a decreasing exponential. Thus, the data illustrates a correlation between higher bending stiffness and greater peak force while running, further illustrating that as cleats deteriorate, the trend as speed increases more significantly represents a decreasing exponential curve rather than a line. This could potentially be a result of extra force required to bend the new cleats in comparison to the older pair, as the new cleats are 25% stiffer than the old cleats and thus require more force to bend to a specific displacement angle while running in comparison to the old cleats. Thus, the old cleats could prove to be better at conforming to the natural motion of the foot.

ACCELERATION ANALYSIS AND JERK CALCULATIONS

Armed with the trend of peak normal force at different cadences, evaluating the acceleration data of the runs reveals more information about speed and acceleration while wearing both cleats. Figure 9 shows an example of an acceleration and force curve with the peak force and push-off periods labelled.

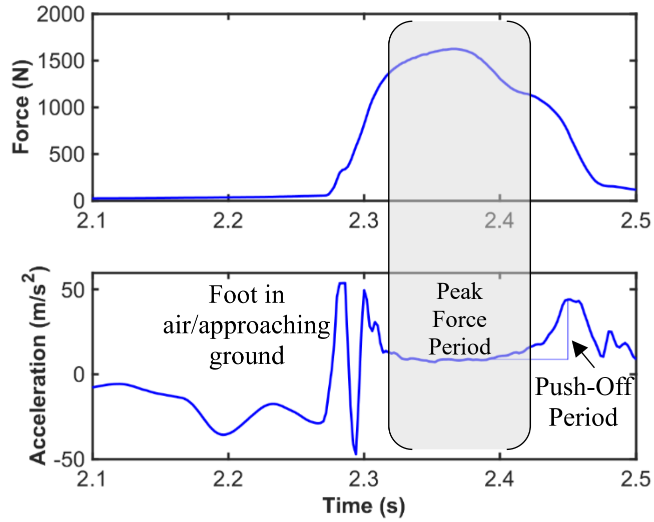


Figure 9: Acceleration and Force data for run 1 with new cleats at 160 BPM. The highlighted portion represents the peak normal force read by the IL-406 FSR and the push-off period directly after provides a change in acceleration and change in time to calculate jerk.

Subsequent evaluation of the average slope of the acceleration curve during this push-off period allows for comparison of jerk values for the two cleats, with comparisons primarily being made at 150 and 160 BPM due to saturation of the acceleration curves at faster cadences. Figure 10 shows the result of jerk calculations for corresponding peak force measurements.

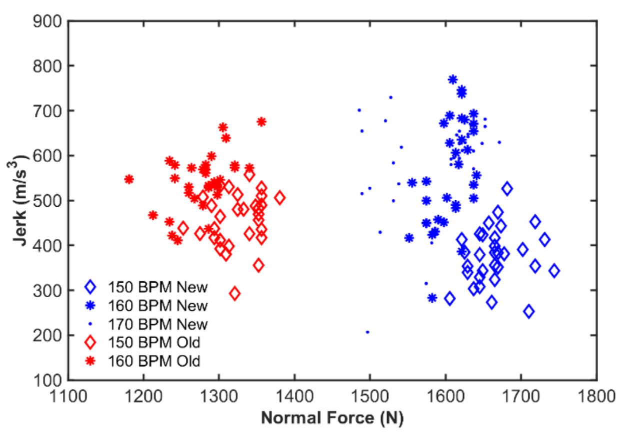


Figure 10: Calculated jerk values for each peak normal force. New cleats shown in blue and old cleats shown in red, both with various symbols delineating cadences.

The scatter plot shows clusters of data for the new and old cleats around similar calculated jerk values, suggesting that the main difference between the new and old cleats is the amount of force required to be transferred to the ground to cause a specific change in acceleration. This could be due to the more pliable nature of the older pair of cleats, allowing force to be transmitted more directly into the ground rather than requiring any sort of bending of a stiffer shoe sole. The lack of a drastic difference in jerk values could be a result of the scope of this project and the constraint of running cadences to represent speed. If a runner is attempting to run at a specific speed to maintain pace at 150 or 160 BPM, it would make sense that the changes in acceleration over the period just after the footfall would be scatteringly similar regardless of footwear choice. On the other hand, physically it is difficult to control the amount of force applied to the ground in stride so the behavior of old cleats in providing better or the same amount of jerk at lower overall forces is striking. The data suggests that old cleats may be more efficient at aiding speed generation as, when wearing the old pair, similar or greater jerk values were calculated while requiring less force.

These jerk values were then averaged and compared versus the cadence at which the run took place, revealing information about how wearing the new and old pair of cleats changed how quickly acceleration took place after the peak force of hitting the ground. Average values with 95% uncertainty and statistical significance are shown in Figure 11.

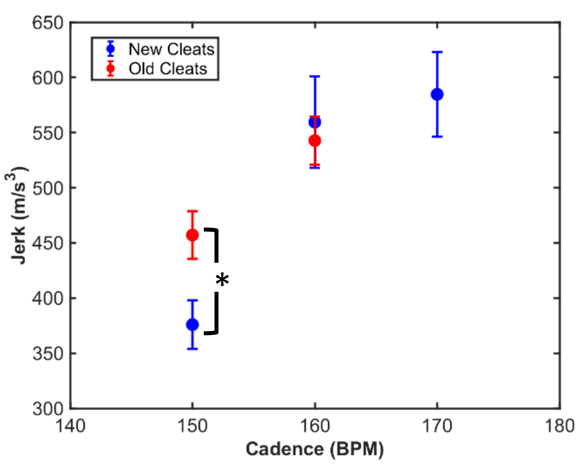


Figure 11: Average jerk values with uncertainty error bars at various cadences. The difference between the means at 150 BPM is significant with 95% confidence – p-value 2.1e-6 – with a hypothesized mean difference of 50.34 m/s^3. Data for old cleats at 170 BPM and all data at 200 BPM was not used due to saturation.

This graphical relationship to cadence reveals that speed generation in this experiment did increase as the controlled cadence increased; although, it is important to recognize that an increase in step cadence does not always indicate running at a higher speed. Two-tailed t-tests reveal a significant difference between the mean jerk values at 150 BPM with 95% confidence – p-value 2.1e-6 – while the difference at 160 BPM is not significant with 95% confidence. The hypothesized mean difference at 150 BPM is 50.34 m/s^3. Although data for the old cleats at 170 BPM was not used in the average jerk calculation due to saturation, it is fair to assume the jerk provided by both the new and old cleats may converge, suggesting that at high speeds there is minimal difference between the amount of speed generated with either. Therefore, the difference among the cleats in measured normal force at the various footfalls suggests that older cleats allow for similar changes in acceleration at lower forces than new cleats. Consequently, it is fair to assume that these lower forces allow for more efficient speed generation that is all around safer for athletes playing explosive sports that require high speed impacts with the ground while running, sprinting, and changing direction. In the context of this study, it is unknown how this measured normal force affects the lower limbs while running; however, less force transferred through the lower leg muscles and knee joints with older broken-in cleats could be safer for athletes all while ensuring a similar aid to speed provided by new cleats. This suggests that athletes desiring fast acceleration changes at higher speeds – due to greater jerk while pushing off the ground – could use old or new cleats; however, those desiring a safer experience while running may want to stick with their old cleats due to lower overall impact forces.

CONCLUSIONS

The above experiments quantified the bending stiffness of both the new and old pair of New Balance Freeze LX Cleats while also measuring the normal force and jerk experienced while running with both cleats. The new cleats proved to be about 25% stiffer with a value of 0.05773 ± 0.00061 Nm/deg in comparison to the old cleats with a bending stiffness of 0.04610 ± 0.00031 Nm/deg when displaced by a 1.5kg hanging mass.

The difference in stiffnesses corresponded with a significant difference in normal force experienced while running at various step cadences representing different constant speeds. Wearing new cleats resulted in higher average normal force values than the old cleats for every running cadence, possibly a result of extra force required to bend the new cleats in comparison to the older pair, indicated by their different bending stiffnesses.

In addition to this force analysis, jerk values obtained from acceleration data immediately following peak forces in 150 and 160 BPM runs revealed that the age and wear difference of the cleats mainly resulted in differences in measured normal force with smaller, more insignificant differences in changes in acceleration measured as the foot leaves the ground in stride. The average calculated jerk for old cleats were greater than new cleats at 150 BPM by about 13% but not at 160 BPM as the confidence intervals for old and new cleats overlapped around similar means. Two-tailed t-tests reveal a significant difference between the mean jerk values at 150 BPM with 95% confidence – p-value 2.1e-6 – with a hypothesized mean difference at 150 BPM is 50.34 m/s^3. This suggests that at lower speeds, the old cleats provided a greater change in acceleration at lower impact forces, indicating a safer running condition for athletes with respect to the amount of force being absorbed by lower leg muscles and knee joints. As speed increases, the difference is insignificant and both cleats provide similar jerk values while the old cleats continue the trend of doing so at lower normal forces, once again proving to match the speed provided by new cleats but at safer normal forces. Consequently, athletes desiring fast acceleration changes at higher speeds could use old or new cleats; however, those desiring a safer experience while running may want to stick with their old cleats. Although this experiment only involved one specific athletic shoe, further analysis could reveal more interesting behaviors in straight-line running and changing direction that would inform design for speed and safety in cleat soles.

ACKNOWLEDGMENTS

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