Redesigning soccer cleat outsoles to reduce ACL injuries in female soccer players

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***Abstract*— This research study aims to redesign soccer cleats for female soccer players to reduce the likelihood of anterior cruciate ligament (ACL) tears. Females are up to eight times more likely to tear their ACL in comparison to males, and soccer cleats are mainly designed for men with women's cleats lacking comfort and performance. We propose an alternative design by varying the density of the outsole to relieve pressure off the knee. Our design redistributes the forces on the foot to achieve an optimal valgus and knee flexion angle, putting female soccer players less at risk, thus, reducing the forces that lead to ACL injuries. Seven different outsole density patterns were designed based on the Nike Premier FG 3 and then printed with Ultimakers out of thermoplastic polyurethane (TPU) using support blockers in Cura. Each pattern was tested on five athletic young adult females. The knee flexion and valgus angles were measured using a virtual reality tracking system as the subjects performed actions of walking, running, and jumping.**

I. Introduction

Female athletes are at a significantly higher risk of anterior cruciate ligament (ACL) injuries compared to their male counterparts, with the likelihood being up to eight times higher [1]. The underlying cause for this difference remains unknown, although various biological and socioeconomic factors could be contributing to the problem. For instance, female athletes are frequently under-compensated relative to their male counterparts, even when they perform better [2]. As a result, they may have inferior training facilities and coaching, which could lead to inadequate exercise of the required muscles [3].

Additionally, females have numerous biological differences, however, there is little agreement among research studies regarding which of these differences contributes to an increased risk of ACL injury. One possible explanation is that, on average, females have a greater quadricep angle and a higher quadricep-to-hamstring ratio [4], which can lead to overextension of the knee ligament and increase the risk of injury. Another possible factor is that some studies have found that females are more susceptible to ACL injuries during specific stages of their menstrual cycle [5]. For the purposes of this research project, we focused on just one of the biological factors: the pelvic width to femoral length ratios.

On average, females have a larger pelvic width to femoral length ratio. One study found the ratio was 0.73 in males and 0.77 in females [5]. This larger ratio was found to be a predictor of high knee flexion and valgus angles [6], which indicates a higher risk of ACL injury [4].

Assuming that high knee flexion and valgus angles are the primary reasons females are more likely to injure their ACL, this research study aims to minimize these injuries in soccer players. We chose soccer as the focus of our study since it has the highest reported frequency of ACL injuries among sports [7].

In order to reduce the risk of ACL injury in soccer players, we have redesigned the outsole of soccer cleats. A study has revealed a strong correlation between cleat design and ACL injuries [8]. In addition, our interviews and surveys with female collegiate soccer players have shown that many of them wear male soccer cleats, as they believe these cleats offer better performance. Therefore, we hypothesize that designing a soccer cleat specifically for females, with a consistent shape and stud pattern but produces minimized knee angles, would effectively lower the likelihood of ACL injury.

In order to achieve this goal, we conducted a research study to test the impact of varying the density of a soccer cleat's outsole at different regions of the foot. Previous research has shown that altering outsole density can influence peak flexion angles and pressure points on the foot, which can have implications for the knee [9]. However, this study only examined male participants and used outsoles with a uniform density. To address these limitations, we focused on the areas of the foot that experience the most stress and varied the density of the outsole at these regions. By doing so, we aimed to identify an optimal density pattern that would result in the lowest knee angles in female soccer players.

For this study, a 3D model was created of a popular soccer cleat worn by many collegiate athletes, as shown in Figure 2. Then, this model was 3D printed out of TPU rubber with varying outsole density at different areas of the foot. Next, the 3D printed outsole was attached onto the existing soccer cleat, as seen in Figure 1, to conduct tests measuring the knee flexion and valgus angles during typical soccer movements. We tested 5 female participants and 7 different variations of soccer cleat outsole density patterns.

There were major design constraints in the experiment. The outsole that we based the 3D model on constrained changes that were made in the outsole that was tested. The size of the 3D printer changed the way that we printed the outsole. More variations would have been tested, but time was a large constraint. Additionally, limitations on who could participate in the study prohibited testing a larger sample size of individuals.

Fig. 1. Prototype of 3D Printed Outsole Attached to Soccer Cleat.

II. Methods

A. Nike Premier 3 FG

In order to isolate density variation as the only changing independent variable in this study, the outsole was modeled in SolidWorks based off an existing soccer cleat on the market, the Nike Premier 3 FG. This shoe was chosen because it is widely used and popular among soccer players. A side-by-side comparison of the designed model and the original is shown in Figure 2.

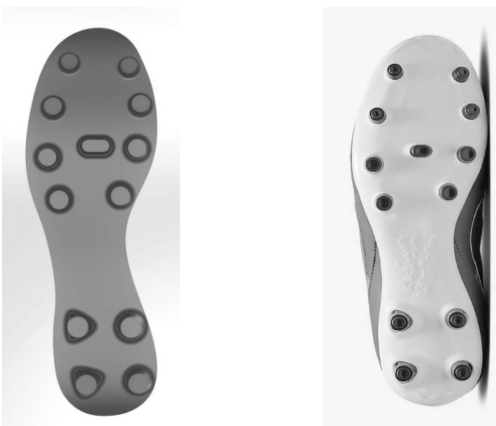

Fig. 2. 3D Model Created of the Nike Premier 3 FG Cleat

B. Finite Element Analysis

1) Boundary Conditions: The Free Body Diagram (FBD) for a human's foot, tibia, and ACL is shown in Figure 3. In this assembly, running loads are being applied on the bottom of the cleat, which translates to the tibia, and then to the femur. This connection between the tibia and femur primarily consists of the patella and ACL, as shown in Figure 4. This clearly shows how the GRFs on the foot translate to normal forces on the tibia, and therefore, forces from the tibia on the ACL. In this way, GRFs translate to forces on the ACL.

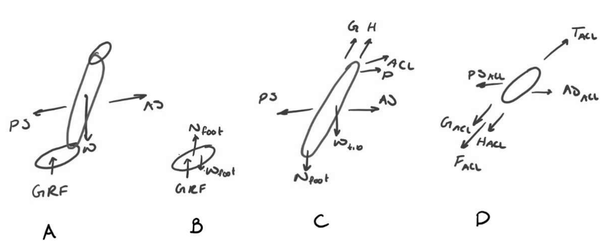

Fig. 3. A) FBD of assembly of foot, tibia, and ACL, B) foot FBD, C) tibia FBD, D) ACL FBD

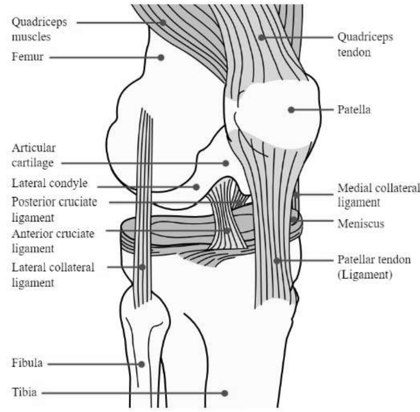

Fig. 4. Diagram of ACL

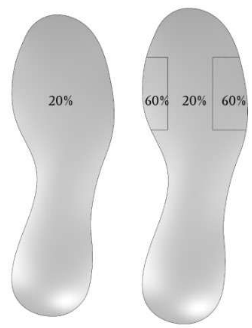

Fig. 5. Outsole Geometries

Due to this and the results of the Pilot Study [9] in Figure 6, the geometries chosen for the analysis are shown in Figure 5. Since the resultant peak pressures from the Pilot Study occurred in the ball of the foot and center of the outer foot, the density was varied here for the geometries in the FEA to better understand the impact of this variation in density pattern on stress values across the top of the outsole due to running loads.

The forces applied to the traction boundary conditions were estimated to represent the most severe running loads that the outsole could encounter, as shown in Figure 3. The figure illustrates how ground reaction forces (GRFs) can translate into forces on the ACL. The values for the running loads to be applied on the outsole are shown in Figure 6, as well as the regions of the foot that the pressure was applied to.

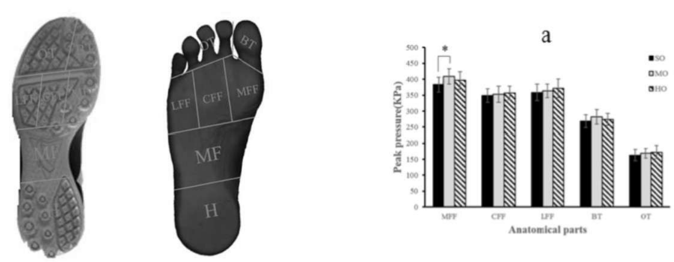

Fig. 6. Regions of the foot outlined in Pilot Study and running loads on different parts of the foot measured in Pilot Study

As shown in Figure 7, the traction loads found from the Pilot Study were applied directly to the bottom of the studs that were located in the regions from Figure 6. Since this is the part of the outsole and the whole shoe that makes direct contact with the ground, it is logical that the force is applied directly there.

The displacement loads for this study included a fixed support along the top of the sole, as shown in Figure 7, to simulate the fact that the sole is unable to move against the user's shoe and foot. Additionally, the displacement parallel to the face of studs was restricted, simulating the instant that the user's foot hits the ground, when the studs can only move axially.

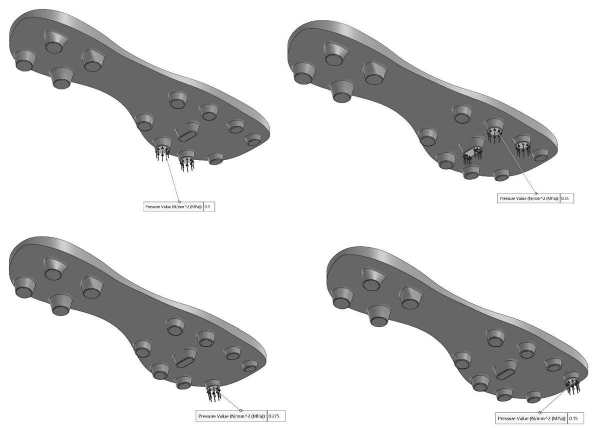

Fig. 7. Traction boundary conditions exerted on the bottom of the outsole studs with loads from the Pilot Study

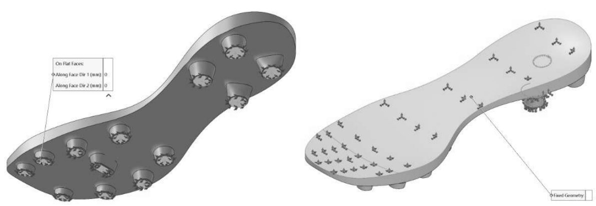

Fig. 8. Displacement loads applied, showing the planar restraints on the studs (left) and the fixed support on the top of the outsole (right)

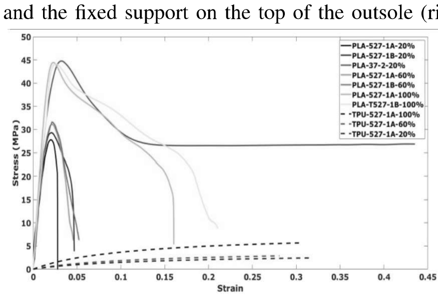

Fig. 9. Material properties for TPU at 20% and 60% density are given by the blue and red dotted lines, respectively

2) Materials: The TPU material properties of various densities in Figure 9 were used and applied to the geometries shown in Figure 5. Custom materials were made in SolidWorks with the corresponding density, elastic modulus, and Poisson's ratio collected from a research study [10]. For the single density geometry in Figure 5, the 20% material was applied. For the multi-density part, the 20%, 60%, and 20% materials were individually applied to the three parts of the assembly, and then mated. This is similar to the process of assembly for the physical outsole for the project.

3) Set Up and Results: The von Mises stress plots are shown in Figure 10 which shows the points the material may fail under the running loads. From the plot, it is clear that the fillets on the studs are most likely to yield.

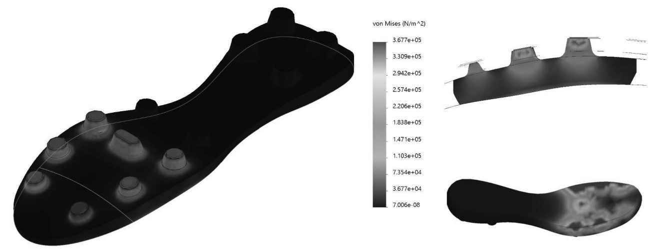

Fig. 10. von Mises stress profiles for single density geometry (left) and multi-density geometry (right)

For this analysis, we are also interested in the relative differences between the two geometries in Figure 5 to see if there is a difference between the distribution of stress due to the difference in density patterns. This was done by probing a split line across the exact same location on the two geometries. The stress results across this line are given in Figure 11, showing that the relative stress is lower along the line on the custom density pattern geometry. This shows that the varying density has a positive effect on GRFs, and therefore, minimizes the runner's risk of tearing their ACL.

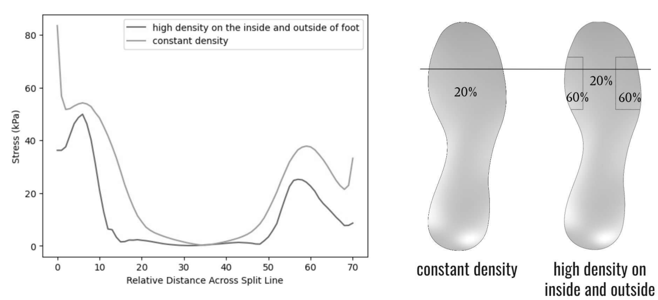

Fig. 11. Geometries analyzed with matching split lines and corresponding stress across the split lines

C. Density Patterns

A total of 7 density patterns were printed and tested as shown in Figure 12. These densities ranged from 10% to 50% infill to test a range of low to high stiffness.

Fig. 12. Different Density Patterns Tested

D. Cleat Assembly

Each iteration of the outsole was 3D printed out of TPU rubber using Ultimaker printers. The dual density outsoles utilized the support blocker feature in Cura to print at a different density than the majority of the print. The outsoles were also printed in half along the vertical axis due to printer size constraints.

The original outsole of the Nike Premier 3 FG was removed using heat and physical force. After doing so, each 3D printed outsole was glued and attached to the shoe using Shoe GOO. To replace each outsole, heat was applied with any necessary physical force.

E. Experimental Design

The experiment was conducted on 5 athletic females in their early 20s. A SteamVR system with 4 VIVE trackers was used to measure and record locations to calculate knee valgus and flexion angles. One tracker was placed on each hip, one tracker was placed above the knee, and one tracker was placed above the ankle. The trackers were tightly attached to their respective body part using velcro straps.

A trial consisted of 2 laps walking, 3 laps running, and 10 jumps in place. One lap is considered to be back and forth across the room. Data was measured and recorded by the Origin using Vicon software. SALTED sensored insoles were also used in each trial as part of the experimental setup. They were paired with the SALTED Training app and the corresponding foot pressure distributions of the trials were measured using the app. However, the precise results of the pressure distribution were not important trial-by-trial, but just used to validate the FEA resultant pressure distribution.

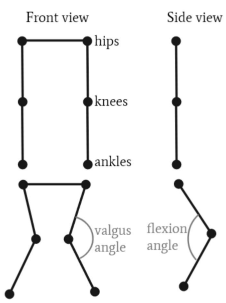

Fig. 13. Knee Angles- Front and Side View

Fig. 14. SteamVR System with VIVE Trackers on Test Subject

F. Calculating Knee Angles

The experiment was always set up for the test subject to walk along either the x- or y- axis. This was decided in order to keep the angle calculations simple and in the two-dimensional space. If walking on the y- axis, the valgus angle would be calculated using the x- and z- coordinates, while the flexion angle was calculated using the y- and z- coordinates. For a few trials, the axes were flipped so that the walking direction was on the x- axis, so the valgus angle would be calculated using the y- and z- coordinates, and the flexion angle with x- and z- coordinates. The angles were calculated using vector calculation as shown in Eqn. 1.

$$\theta = arccos(\frac{\mathbf{a} \cdot \mathbf{b}}{|\mathbf{a}||\mathbf{b}|}) \qquad (1)$$

III. Results

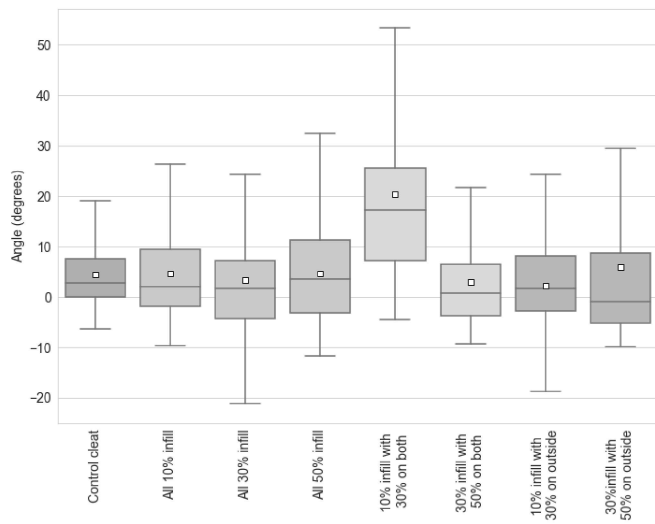

Fig. 15. Boxplot distribution of valgus angles from running data

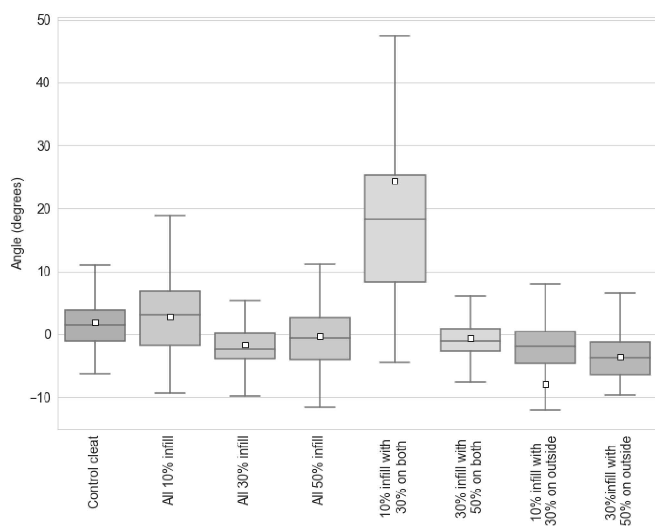

Fig. 16. Boxplot distribution of valgus angles from jumping data

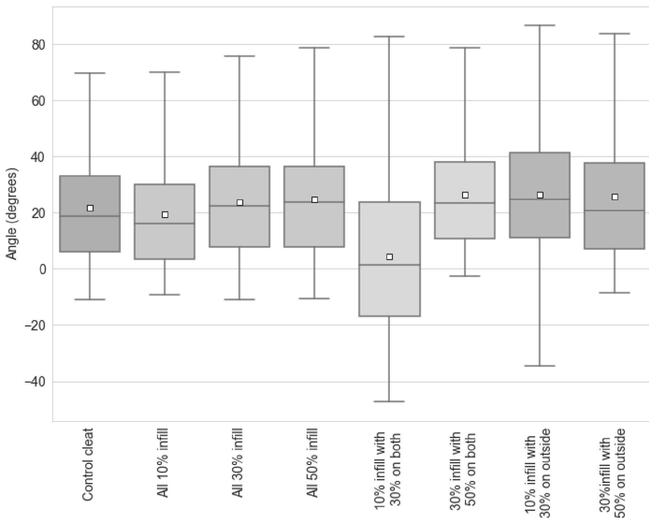

Fig. 17. Boxplot distribution of flexion angles from running data

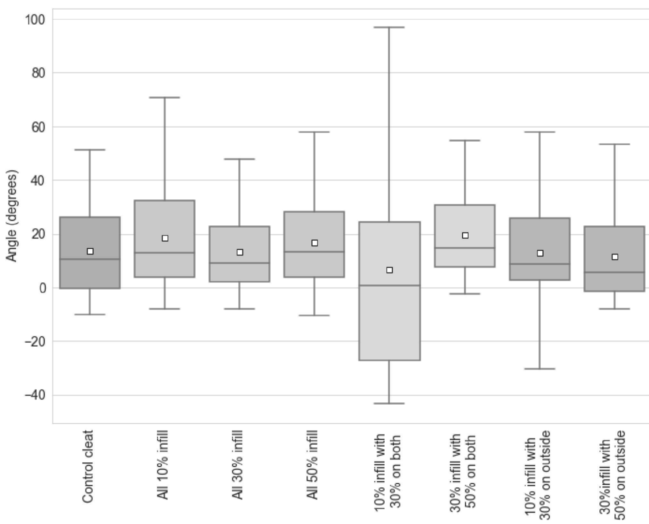

Fig. 18. Boxplot distribution of flexion angles from jumping data

IV. Discussion & Conclusion

A. Interpretation and Comparison of Results

The results we obtained from our running and jumping trials were graphed as distribution boxplots, as seen in Figures 15-18. Running and jumping provided more data points due to the increased amount of movement in comparison to walking, giving us a clearer idea of how the density affects movement. Every distribution plot gives us a range of valgus and flexion angle values for each density patterns we tested, in addition to the values obtained from the control cleat for comparison.

This research study ultimately showed us that the 30-50 both multi-density outsole had the best results. By examining the boxplot distribution for valgus angles, we see that the 30-50 both outsole distribution resulted in the smallest angle range, supporting our hypothesis. By having a smaller, controlled angle range, it is assumed that the likelihood of an ACL tear decreases, given that there's less of a chance of the knees buckling inward. This is an example of a density pattern where a higher density was added in the MFF and LFF regions of the foot, in accordance with the pilot study we followed [9]. The flexion angle boxplots do not show much variation in the distributions between most outsoles, however this is expected as the actions themsevles remain constant throughout trials and should not vary as much compared to the valgus angles.

B. Study Limitations

Since this research study was limited to only five female test subjects, a larger sample size would be necessary to confidently establish the significance of the differences observed among the shoes tested. Furthermore, we were not able to determine whether the design itself was dependent on sex, given that all the subjects were female.

Furthermore, the research study did not take place in a soccer setting and was instead confined to a lab due to the use of the Steam VR tracking system. The lab had a tiled floor and was much smaller than a typical soccer field. The difference in friction between tiled floors and grass could affect the knee angles observed in actual play.

Another limitation is that the VIVE trackers were placed directly above the knee and ankle joints. While this provided a close approximation of the knee angles for our study, it is not exactly equal to using the points of the joints themselves.

Additionally, because of the time limit on testing, some cleats were not tested on all 5 subjects due to scheduling conflicts. However, each cleat was tested on at least 3 people.

In terms of 3D printing, the outsoles had to be printed in half due to size. However, this meant in the middle there were walls, which technically changed the density in that area. Additionally, the design was modeled after images of the cleat, so it was not the exact design of the outsole of the Nike Premier 3 FG shoe. Furthermore, the control cleat was also made out of plastic studs versus rubber studs. While the material of the studs can vary between cleats, this was a difference in terms of our designed cleat and the original.

C. Errors and Shortcomings in Analysis

The main limitation of the Finite Element Analysis is that there is not enough published information about the material properties of TPU at different densities. Since TPU itself is not even a given material in SolidWorks, the material properties were found from the study [10]. From the graph, the material's ultimate strength and elastic modulus were found at different infill densities, while the density and Poisson's ratio was referenced from online sources[11]. This limited information could have led to differences in the overall stress distribution, as well as the stress plot over the split line. This could have been solved by conducting a standard dogbone test of the printed TPU at different densities to find the elastic modulus and Poisson's ratio.

Another limitation arose from the boundary conditions, which may not have best simulated the conditions while running. The top surface of the outsole is, in fact, able to bend and move during running, but this would have immensely complicated the analysis.

The traction boundary conditions could have also been more precise, but were taken from the Pilot Study, which offered pressure data taken from men running. However, this was collected from the insole of a turf shoe, not the outsole. This could be different from how the outsole specifically experiences GRFs. However, due to limited studies on ACL damage and GRFs while running, this was the best use of the existing data.

The raw data collected from the VR system occasionally had a few milliseconds where the data collection malfunctioned and the calculated angles would then peak extremely quickly, unrealistically. However, in order to exclude this data, outliers were excluded from the box plots. An outlier was determined by the default setting for the seaborn library box plots, which is 1.5 times the interquartile range. However, it would have been more accurate to go through the data and filter out the abnormal, unrealistic peaks rather than excluding outliers.

It is possible that showing the distribution of the resulting angles alone is not sufficient in determining whether or not these patterns induce safe knee angles. Our results also only take into account the 7 patterns that we were able to test, and comparing the 30-50 outsole to other iterations with densities much higher that 50% might not render it to be the optimal option. However, it did seem to perform better than the control cleat in terms of outputted angles in some cases.

Since the distributions were not normally distributed, it was decided that t-tests to compare distributions would not be extremely useful. This is also because there were 7 distributions to compare, and the tests would only provide if there was a difference or not, but not determine what was better.

D. Improvements

In the future, the limitations discussed above could be improved upon for more consistent and feasible results.

Overall, since this analysis is part of a research study exploring the effect of cleat outsoles on susceptibility to ACL tears, there are many other considerations that could be made in the future. Different geometries and density patterns could affect one's valgus angles, and therefore, their risk of ACL tears. This study could be repeated to study the effects on stress results of a harder density at the heel, for example.

Also, a lower stiffness ratio could be analyzed with this same geometry, where the difference in the stiffness is minimal. For example, 40% and 60% density geometries could be analyzed rather than 20% and 60% to see how the density differential impacts overall stress and stress along the split line.

The data collection could also be improved by increasing consistency. The number of test subjects could be higher to increase the reliability of data and the data could be taken on the same day to reduce differences in the VR setup. This increase in resources and time would lead to more reliable results.

E. Conclusion

To conclude, this research study aimed to validate our hypothesis which states that varying the density in the cleat outsole would impact the knee valgus and flexion angles, allowing us to find a density parttern that would result in smaller angles, which would reduce the likelihood of an ACL tear. We were able to produce 7 density pattern prototypes and compare their results to that of a control cleat. The prototypes were 3D printed using TPU, and the density changes were made in foot regions dictated by existing literature. The setup consisted of a VR tracking system which provided the location of the knees, hips, and ankles in each trial. The angles were then calculated using Python code and were compared through boxplots.

We found that our 30-50 (both) outsole produced the safest angle range, and validated our hypothesis that density variations do in fact have an impact on valgus and flexion angles.

Overall, this analysis prompts exciting work in women's sports medicine and aims to lay groundwork for future research linking ACL tears and cleat design.

V. Appendix

Listing 1. Knee Angle Calculations in Python script

```python
import pandas as pd
import numpy as np

#function for angle calculations
def findAngle(x1,x2,x3,y1,y2,y3):
    #create vectors
    ba_x = x1-x2
    bc_x = x3-x2
    ba_y = y1-y2
    bc_y = y3-y2

    #make vectors into dataframes
    ba = pd.DataFrame({'ba_x': ba_x, 'ba_y': ba_y})
    bc = pd.DataFrame({'bc_x': bc_x, 'bc_y': bc_y})
    #dot product
    dot = np.dot(ba, bc.T.values).diagonal()

    df = ba.join(bc)
    df['dot'] = dot
    #calculate magnitudes of vectors
    df['ba_mag'] = np.linalg.norm(
                    ba[['ba_x', 'ba_y']].values,
                    axis=1)
    df['bc_mag'] = np.linalg.norm(
                    bc[['bc_x', 'bc_y']].values,
                    axis=1)

    df['mul_mag'] = df.ba_mag*df.bc_mag #denominator
    df['divi'] = df['dot'].div(df.mul_mag)
    df['ang'] = np.degrees(np.arccos(df.divi))
    return df[['ang']]

#angles were calculated based
#on the natural angle from Tpose
def normalizeAngles(tpose, df):
    x = np.mean(tpose) - df
    return x
```

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