Examining Tennis Footwear Wear Patterns for Injury Prevention

by
Alec Westbrook

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Chemical Engineering
(Honors Associate)

Honors Baccalaureate of Science in Innovation Management
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Presented June 4, 2020
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Alec Westbrook for the degree of Honors Baccalaureate of Science in Chemical Engineering and Honors Baccalaureate of Science in Innovation Management presented on June 4, 2020. Title: Examining Tennis Footwear Wear Patterns for Injury Prevention.

Abstract approved:____

Ben Mason

Tracking footwear wear patterns is vital to the footwear industry. In the game of tennis, there are several court surfaces that produce unique wear patterns on footwear that are constantly changing according to the following factors: level of competition, level of experience, coordination, age, height, weight, and more. By tracking these footwear patterns in athletes across aging populations, this allows athletes and footwear manufacturers to gain clearer insight into new developments to be made from existing technologies.

Through pioneering efforts in file sharing, data-driven insights, and user feedback, the current era of sport provides resources necessary to produce cutting edge footwear products. Monitoring these behaviors helps athletes stay healthy, track their performance, and reduce injuries sustained during sport. As further research is conducted, more insight will be gleaned in order to provide products that offer characteristics athlete populations seek out.

Key Words: Footwear, wear patterns, athlete populations, pronation, supination, biomechanical assessment, image analysis.

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Alec Westbrook, Author

Table of Contents

Background
Across all sports, athletes' personal equipment and footwear impacts their performance and endurance. Specifically in the sport of tennis, longevity is a major contributing factor that allows athletes to enjoy the sport throughout the span of their adult lives. By maintaining and protecting this associated equipment, this increases the likelihood that athletes will continue to play the sports they love and mitigate risks of injury. Proper maintenance of this equipment requires analyzing how equipment and footwear wear and deteriorate throughout use. In the game of tennis, this action can be as simple as checking the bottom of a pair of tennis shoes or an athlete's racquet over time. Tracking relative conditions of personal equipment serves as a reference point to provide insight into gameplay behaviors. In the sportswear and footwear industries, this phenomenon is known as wear pattern documentation. For the purpose of this document, all further mentions of wear pattern documentation will be in reference to footwear.

Wear pattern documentation is an emerging data-driven technology that provides feedback for manufacturers to derive the newest innovative products for athletes. In high impact sports such as endurance running, cross country, football, basketball, soccer, and track and field, these insights have become heavily analyzed metrics to help athletes excel and combat injuries. Further data collected in independent studies by researchers from these organizations as well as independent research efforts link footwear geometries to long term biomechanical effects on the body. Originally documented in biomechanical studies centered around long distance running, effects of pronation and supination have showcased forecasted injury and wear patterns. At the emergence of this insight, companies have made use of information sharing and product development technologies to streamline how footwear products are manufactured today.

As with the advances in footwear for the aforementioned high impact sports, similar developments have also been made in the tennis footwear industry. However, these innovations in tennis footwear act as laggards compared to other sport counterparts in the diffusion of innovation curve[1]. This is likely due to a number of factors that contribute to outsole construction in tennis footwear.

Tennis footwear highly varies in accordance with the court surface that athletes are playing on, in order to provide necessary characteristics. The three common court surface types that tennis athletes play on are hard court, clay court, and grass court. Each of these three surfaces offers unique characteristics to the gameplay style and the rate at which footwear is worn down. Grass courts are highly uncommon in the United States, but offer the most forgiving and softest surface to play tennis on. Clay court is the next most forgiving in regards to court density. However, this court style produces a thin dust film over the court surface, allowing athletes to slide more easily into various shots but decreases mobility. Lastly, hard court surfaces are the least forgiving, generate faster ball speeds, and provide the most grip and traction for athletes. Each of these surfaces presents different design challenges for footwear manufacturers as each of these surfaces showcase the effects of pronation and supination very differently than one another. Due to the availability of hard court surfaces in the United States and the characteristics that the surface transfers on footwear, hard court provides the greatest amount of wear pattern feedback for footwear studies in various athlete populations[2].

Finally, a contributing factor to the rate at which different sports footwear decline is the style of gameplay the athlete participates in. For example, it is likely that an athlete that engages in quicker, more frequent competition level will wear through a pair of footwear faster than an occasional leisure player would. However, there is a disparity in the data provided for these research factors, and this phenomenon can produce more robust results than conceptualized. Athletes move their feet very differently when playing tennis as they age, evolve to accommodate injuries, styles of play, and more. This insight is currently missing from published research, and can provide useful links into common injuries sustained from wear patterns in athletes' footwear.

Introduction

In order to model wear pattern effects of different populations of tennis athletes, a comprehensive study evaluating relative wear and recent injuries sustained by athletes was conducted. All athletes in this study were athletes that primarily played on both indoor and outdoor hard court surfaces. The project objective of this research study aimed to quantify how these footwear wear effects change in aging tennis athletes. Once these results were obtained, it was decided that a biomechanical assessment of various types of athletic stride were to be collected in order to showcase the distribution of gait tendencies when approaching various tennis strokes. This supplementary step provided feedback on footwear preparation for shots with ample preparation time.

All athletes were contacted to gauge their interest in better understanding their individual footwear wear patterns. However, due to the social distancing effects of COVID-19, this assessment occurred with a limited population of 5 athletes. Significant factors were still collected despite this limited athlete population size, and are described in further detail in later sections. Research for this study was composed of three individual components to model the effects of wear pattern tendencies in tennis athletes.

The first component was a Google Form survey that asked participants to provide information in three sections. This survey asked users to provide general information, information about preferred footwear characteristics, and previous injury history while playing tennis or another sport.

The second component of research collection was image analysis of submitted photographs of athletes' tennis footwear outsoles. Participants were asked to submit a photograph to an email address or routing phone number that would keep their identification anonymous, but still showcased their age so that they could be grouped in the correct athlete age population. Images by population were compiled over one another to produce a wear pattern heatmap that identified normalized regions of excessive wear in both athlete populations.

The final component to this research project was conducting a biomechanical assessment of athletes from both populations to get live action footage of athletes pronating or supinating through their strides. This footage was used to show how footwear varies between populations when preparing for various common groundstrokes.

Athletes in question for this study represented two populations due primarily to the age diversity in the number of human participants, as well as the level of play that various athletes engaged in. By grouping these athletes in two different populations, this provided unique factors and correlations that could be derived from group statistics. For example, common wear pattern areas or common injuries sustained by different populations could be described by analyzing data from individual responses. Ultimately, correlations for heavily worn areas on various footwear outsole styles were compiled and overlaid to provide insight into how different populations wear down frequent regions in footwear outsoles.

Initial Participant Survey

The first research component for this project was a Google Form survey that asked participants to provide information for 27 research questions broken down into three sections (*Appendix D*). The reason that a Google Form format was chosen to administer a survey rather than others was primarily due to the Google platform's accessibility, shareability, and ease of information storage. Logistically, this would allow a greater number of users outside of Oregon State University to access the form and provide responses to the survey questions. Due to the form's accessibility, 21 responses were provided from athletes ages 22 to 75 years old. Also, this format allowed participants to individually go through each section and answer questions relative to different components relative to the research survey. The survey was segmented into three individual sections addressing unique study parameters.

The first section asked participants to include demographic information such as height, age, ethnicity, gender, prior tennis experience, level of competition, and more. These were asked in order to establish a baseline understanding of the diversity and breakdown in each population of athletes. Also, these questions provided insight into how the populations should be grouped in order to visualize different trends from footwear wear pattern data.

In the second section, questions were centered around tennis footwear preferences. These questions asked athletes to reflect on their preferred tennis footwear brands, characteristics that they look for in tennis footwear, and regions on the outsoles with the most wear. These initial factors framed follow up discussions and questions to ask in the follow up biomechanical assessment. An important question in this section of the initial survey was a question that asked athletes to identify the region on their footwear outsoles that was the most worn compared to others. This key insight provided clarification on future methodology that was used to zone the bottom of tennis footwear to identify hot spot wear areas in participants' footwear. This section relied heavily on participant accountability to answer truthfully and honestly, which may have led to information bias by participants when entering in personal data for these questions. Due to the participant sample size and nature that the questions were asked in this study, this phenomenon did not significantly influence results.

Finally, the last section looked to identify previous injury history sustained by participants involved in this study. Questions asked participants to recall the most recent injury sustained, the last injury sustained during sport, and the last injury sustained while playing tennis. Supplemental questions were then asked to gather behaviors of athletes in response to injuries and sustained pain felt while playing tennis. Key questions in this component of the research survey targeted questions centered around body and muscle groups that were frequently injured when playing tennis. The reason that these questions were employed was to possibly identify trends of sustaining injuries to the ankle, knee, or foot groups depending on various wear patterns sustained by either population. Between this injury reporting and the submitted footwear imaging analysis, these factors were correlated with one another to derive relationships that could predict likelihood of athletes sustaining injuries to these areas.

Footwear Image Analysis
Upon completion of the initial research survey, participants were prompted with the following message upon completion of the initial survey:

Thank you for submitting a response! If you feel comfortable please submit a picture of the bottom of your current tennis footwear resembling the picture above to (707)954-7728 or westbroa@oregonstate.edu to be later used in imaging analysis. Thank you!
Figure 1. Overview of response provided to participants that completed the survey.

This final question was asked in order to compile anonymous photographs of the bottom of participant tennis footwear to be used later in wear pattern imaging analysis. This message was posed as a follow-up action rather than another question within the initial survey so that participants could elect to provide an image of their footwear or not. Also, due to the iOS, Android, and other operating system privacy constraints, many cell phones and tablets would not have been able to properly upload the requested image without first uploading it to an associated Google account. In order to maintain the desired accessibility that was necessary for the survey to reach all participants, this feature was elected to be removed and all images provided would be confidential and voluntary.

These images were then sorted by athlete age before being transferred to a localized drive for further analysis. While 21 participants participated in the research survey, 14 provided supplemental images for further image analysis. Fortunately, 8 images from the young athlete population and 6 from the older athlete population were provided, therefore similarly representing both populations.

Once outsole footwear images were sorted accordingly, visual wear analysis was conducted to indicate relative wear conditions by outsole region along the lateral footwear profile. When evaluating each submitted image, four regions on the footwear outsole profile were analyzed in order to quantify popular areas of wear among athlete populations. In order to also assess pronation and supination effects, each of these four regions were split along the lateral length of the outsole profile to generate four regions on the inner and outer profiles of the shoe. Wear conditions were rated on a 1 to 3 scale to catalog conditions of minimal to no wear, median to normal wear, and extreme wear. This scale was used due to established models that currently monitor wear analysis in performance running footwear[3].

However, in order to articulate the results of these wear conditions on athletes' footwear, a theoretical model needed to be constructed in order to normalize the wear effects on each footwear outsole region. This theoretical model was constructed by making use of an equation that calculated the normalized average of wear conditions in each athlete population. Further, this equation analyzed the wear pattern results from each image and calculated the percentage of athletes in each population that would have extreme wear at each footwear outsole region. Eight normalized metrics were tabulated for each of the eight footwear outsole regions outlined above using the equation shown below in *Equation 1*.

Equation 1. *Normalized Average of Extreme Wear Conditions by Outsole Region*

$$WA_{i.outsole} = \left(\frac{\sum_{i=1}^{n} X_i}{3n}\right)(100)$$

**Where:*

WA_i represents the extreme wear conditions score for each outsole region.

X_i represents the individual outsole region wear score on each provided image on a 1 – 3 scale.

n represents the number of responses in each athlete population.

Finally, these summary statistics results were used to construct a heatmap of each of the 8 outsole regions to provide a visual graphic of common hotspots that athletes in each population tend to wear down on their footwear. This heatmap was constructed using the 'heatmap' function in the programming language MATLAB, provided via Academic License through the Oregon State University College of Engineering. MATLAB is a closed-source software application that allows for greater efficiency in conducting repeatable calculations and creating figures and plots. Values used in this script were pulled from a spreadsheet used to calculate the wear average by region in each population, before being overlaid into the heatmap. The script used to formulate this figure is listed below in *Appendix E*. Once wear pattern results were tabulated, it was decided that a further biomechanical assessment of athletes from each population was to be conducted. This was ultimately chosen in order to compare the previously attained wear pattern results to biomechanical tendencies in tennis stroke preparation.

Biomechanical Assessment and Motion Capture

Upon completion of wear pattern analysis for both populations, all participants who submitted outsole images were contacted about conducting an anonymous biomechanical assessment. The objective of this assessment was to gather still image and video content to later be used to model pronation and supination effects in athletes when preparing for common strokes during various styles of gameplay. Although overall pronation and supination wear effects were previously characterized through wear analysis, these patterns could arise throughout various phases during competitive gameplay. By documenting trends of how athletes in each population prepare for common groundstrokes, this would provide correlations between wear patterns during shot set up and commonly sustained injuries.

Of the 14 participants that submitted images for footwear imaging analysis, 5 participants responded saying that they felt comfortable participating anonymously. Due to constraints provided by COVID-19, only 4 of these participants were able to provide still image and video material of their footwork for shot preparation. Two participants from each athlete population were available to provide material for this assessment, outlining common practices that lead to heightened pronation and supination effects along the lateral profile in tennis footwear. These behaviors induce lateral strains on due to footwork and foot placement in shot preparation for common ground strokes.

The 5 groundstrokes that were evaluated in this assessment were common strokes that athletes progress through when playing various levels of competitive tennis. In order to accurately model competitive gameplay, the four athletes that indicated availability for this assessment warmed up for approximately 20 – 30 minutes before progressing through each stroke. The first two strokes (one stroke each to the forehand and backhand sides) were midcourt approach shots that allowed athletes to properly set their feet before making further progress towards the net. The second two strokes were baseline groundstrokes that were completed approximately 5 feet in front of the baseline in order examine the differences in footwork and shot preparation before other common groundstrokes. Finally, the last groundstroke hit by athletes in this assessment was an overhead serve from the baseline on the forehand or deuce-side court (*Figure 2*).

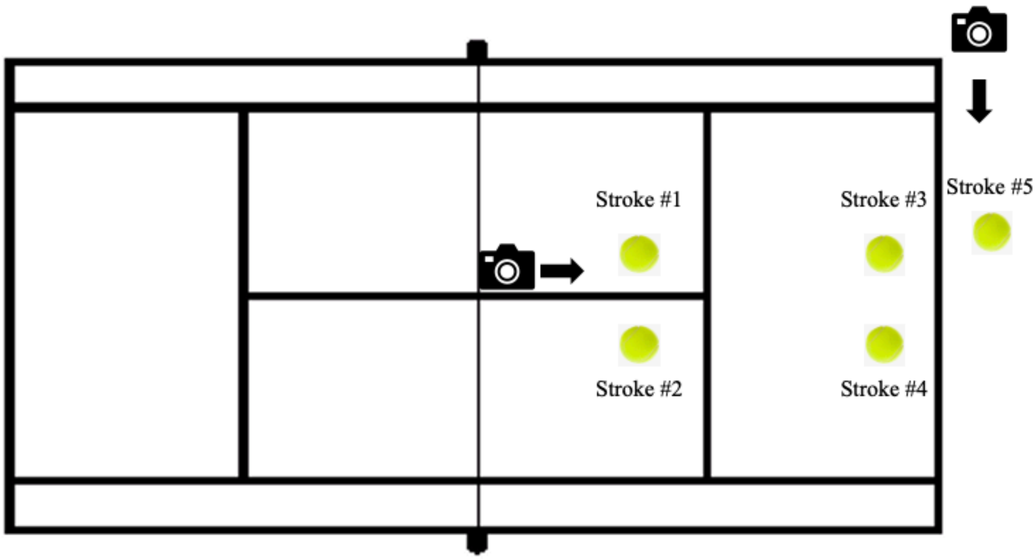

Figure 2. Overview of tennis court layout, camera location, camera shot angles, and locations of common groundstrokes. Athletes were asked to prepare for each of these shots as they normally would during their identified style of gameplay. For Stroke #5, the camera was moved perpendicular to athletes hitting their serve in order to fully account for foot placement and preparation for each shot.

This shot is the first stroke that is hit in order to initiate gameplay in each game, set, and match. Footwork and preparation for this shot is entirely different than other common groundstrokes, as it is much more explosive and dynamic. This shot was thought to simulate instances of extreme stress on footwear and characterize differences between this stroke and other common groundstrokes. Because athletes are exerting more force on their lower bodies while hitting this shot, this could correlate to the phenomenon of athletes in the younger population wearing down the toe of their footwear faster than other regions of the shoe[4]. Upon completion of each of these strokes, results were documented and cataloged to later be used in the research process.

Results and Discussion

Initial Participant Survey

Section 1 - General and Demographic Information

After participants completed the 3 sections of the initial survey, all details and results were compiled to create summary statistics of the population demographic information, preferred footwear characteristics, and previous injury history. In the first section that asked participants to provide general information, the following results were obtained:

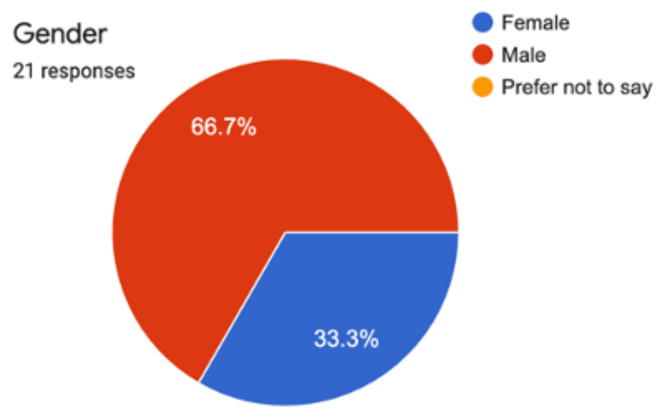

Figure 3. Breakdown of participants by gender. Of the 21 total participants from both populations that submitted responses to this initial survey, 14 were female and 7 were male.

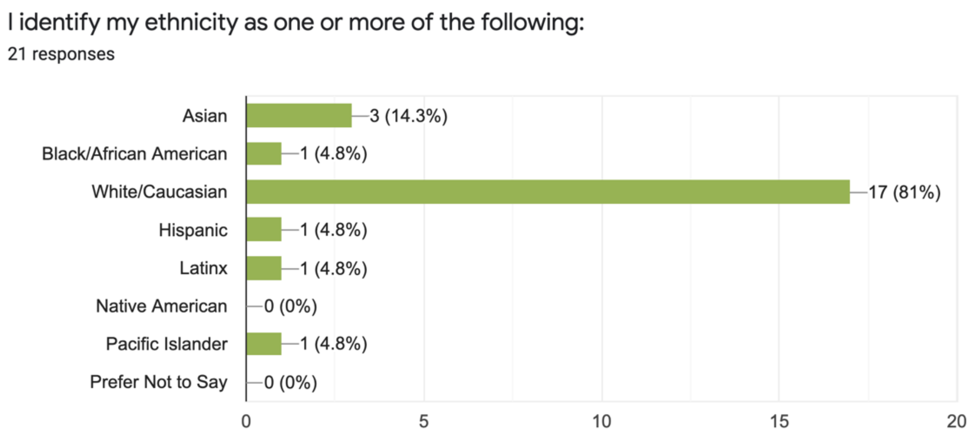

Figure 4. Breakdown of participants' identification of their associated ethnicity(/ies) based on common identifying factors. Each of these associated ethnicity identification options was chosen in order to comply with regulations set in place from other surveys that did not require IRB approval.

In both the young and older athlete populations, there was a similar distribution between the identified genders of athletes, but a disparity in the distribution of identified ethnicity. Only one participant from the older athlete population identified as not White/Caucasian. This lack of diversity could be due to a number of factors. Specifically, this could be the result of the younger population being more willing to participate in a technology-based survey, or the demographic breakdown of tennis players in older populations. Eighty-two percent of tennis players over the age of 55 reported to identify as White or Caucasian[5]. Finally, this could be a factor due to the population that this survey was distributed to as well. Of the older participants involved in this survey, the networks that the research lead introduced the survey to were primarily composed of people who traditionally identify as White or Caucasian.

Overall, this factor should prove to be insignificant for the purpose of identifying and characterizing footwear wear patterns in either athlete population.

In regards to identified gender, there was a similar distribution in the number of female and male athletes in each population. This showed that obtained results between each population would be significant to one another as they would provide similar data by population. Unfortunately, female participants were not accurately represented in the biomechanical assessment and motion capture portion of this research project due to constraints brought on by COVID-19 and lack of responses by female participants in the older athlete population. Fortunately through the conducted image analysis, wear pattern effects were characterized and tracked by gender in each population. Similar to gender, other significant factors that impacted athlete wear patterns were experience level and level of competition played. Results from the associated responses are shown below in *Figures 5 – 6*.

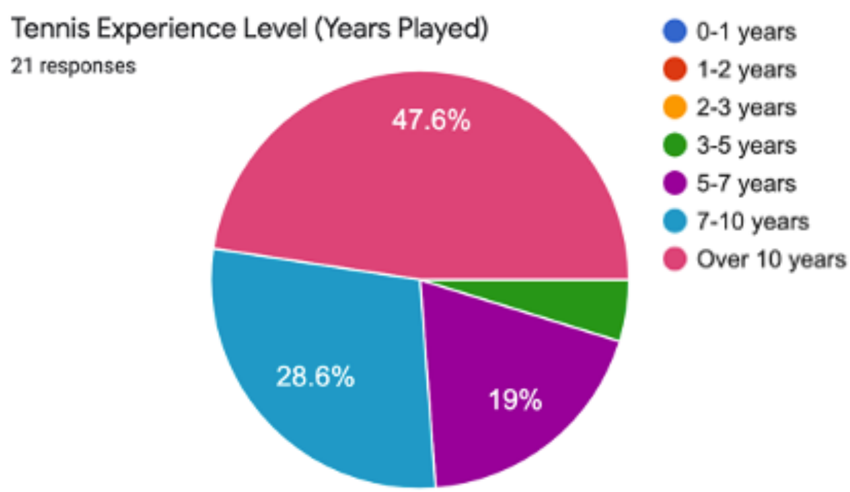

Figure 5. Composition of tennis athlete experience level by number of years played. While most of the older athlete population was composed of athletes that had played tennis for over 10 years, there were similar distributions of experience level in both populations. This demographic factor impacted both populations' relative wear patterns due to more efficient footwork with greater comfortability with the sport.

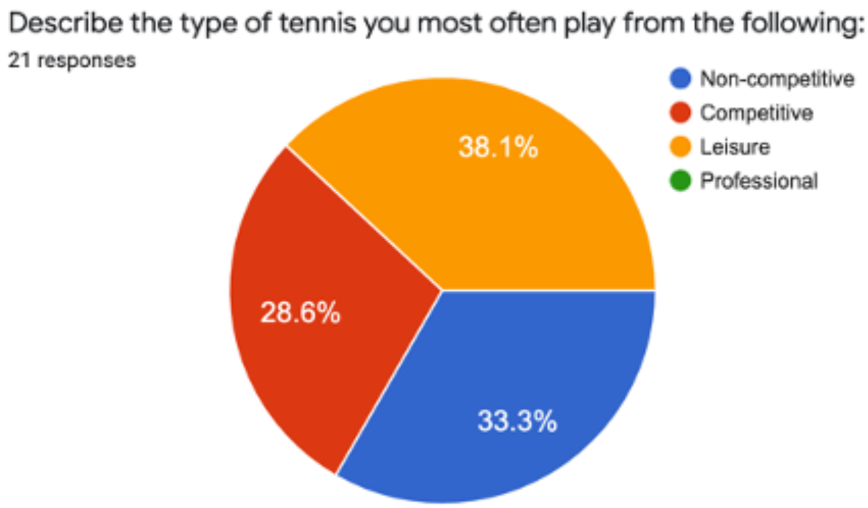

Figure 6. Results from the question asking participants to rate the level of competition that they engage in when playing tennis. Of the 21 participants, 8 designated that their most frequent style of gameplay is leisure. This term was to emulate styles of play normally characterized by participating in drills and improving skills. This term was intentionally left vague in order to have participants choose to characterize their style of play in a particular fashion.

These visual aids illustrate that the majority of athletes that participated in this study have over 5 years of playing experience. Generally, as athletes gain experience playing tennis, they become more efficient with their footwork and more familiar in preparing for common groundstrokes. This results in greater wear on the outsoles of their footwear and common trends reinforced by muscle memory[6]. Also, as competition level increases, the input effort, preparation, and force necessary to hit common groundstrokes increase as well. Therefore, this increased strain could likely result in greater wear on footwear outsoles. Ultimately, these factors provided in the first section of the initial participant survey established a baseline moving forward for further data analysis.

Section 2 – Preferred Footwear Characteristics
In the second section of the initial participant survey, participants were asked questions centered around preferred footwear characteristics when shopping for or playing in tennis footwear. Common brands that athletes preferred, areas of extreme wear, qualities of value, and qualities to be improved were pivotal characteristics that shaped further image analysis and biomechanical assessment moving forward. While various footwear manufacturers have wide product lines, there are certain characteristics that exist between products that greatly appeal to athletes. Preferred tennis footwear results of athletes participating in this study are listed below in *Figure 7*.

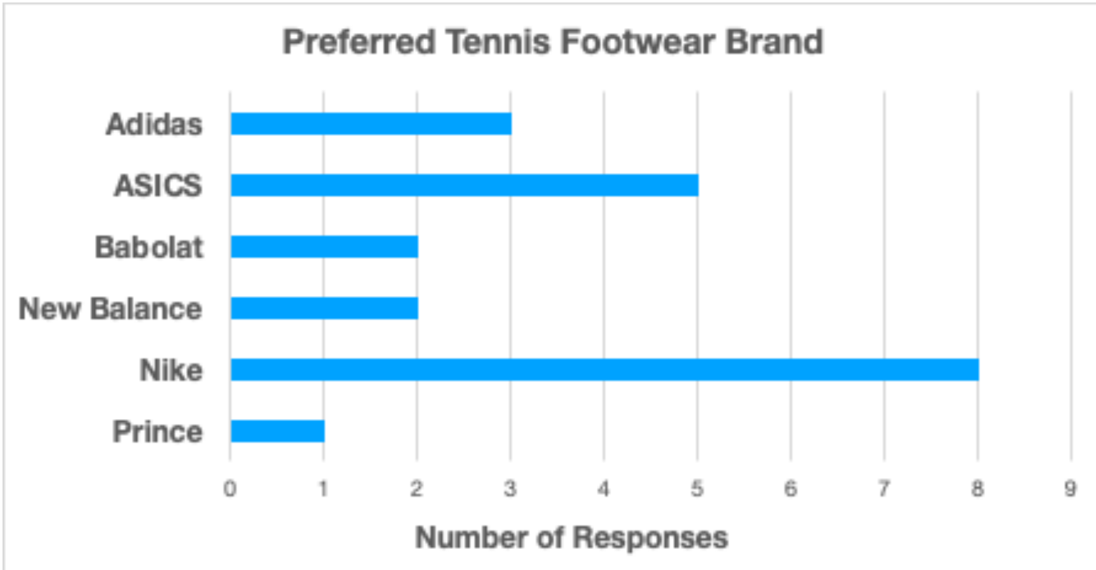

Figure 7. Results of athletes' preferred tennis footwear brands by number of responses. Nike was the most popular footwear manufacturer according to responses from this question. An important note for athletes in both populations is that Adidas, Nike, New Balance, Babolat, and Prince offer both wide and narrow widths for athletes with arch support needs or problems.

Both Nike and ASICS offer wide product lines that incorporate innovative technology to encourage comfort and durability in footwear applications. ASICS specifically emphasizes this focus on innovation, and commits more resources to its tennis footwear product line than all other manufacturers listed above. Each manufacturer has unique products within its product line that support the different needs of athletes. Various characteristics are more heavily emphasized in different products and provide athletes with greater feedback, comfort, and more. In order to better gauge which of these characteristics are more important to athletes, participants were asked to rate their top 3 characteristics that they look for in tennis shoes as well as the top 3 characteristics that could be improved in the shoes that they currently play in. The results of the top 3 characteristics that athletes look for in tennis footwear are shown below in *Figure 8*.

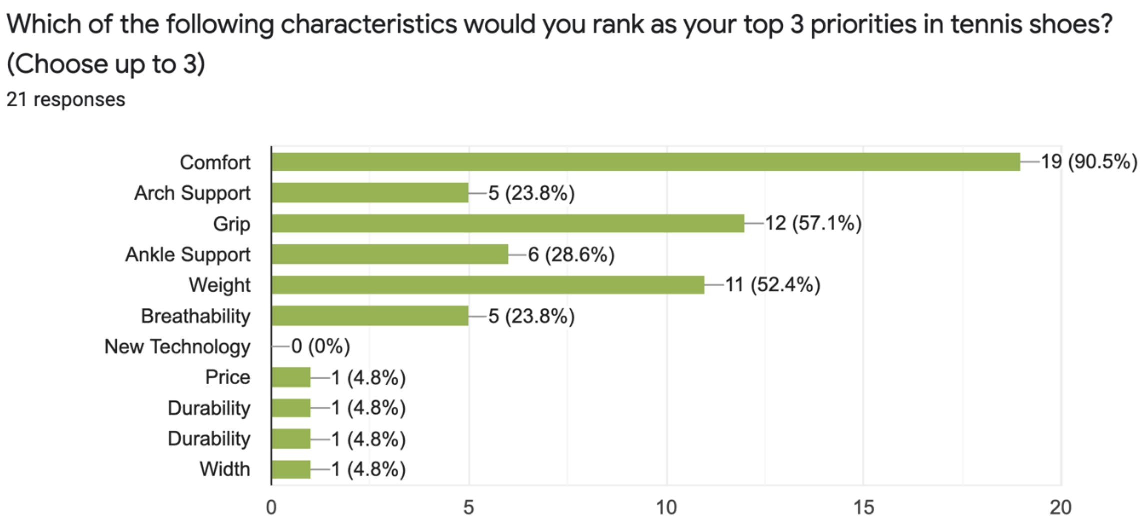

Figure 8. Results from the top 3 priority characteristics in tennis footwear elected by participants in this survey. Of the 21 participants that completed the initial survey, 19 indicated that comfort was a top priority. Second most behind comfort was grip, which can be directly linked to tennis footwear wear patterns sustained by athletes.

Of the characteristic options presented in this survey, surprisingly durability was one of the lowest preferred qualities. Interestingly, those that presented signs of extreme wear upon submitting footwear photographs for further imaging analysis were among those that elected to omit grip from their top 3 preferred characteristics. There was a greater distribution of qualities that athletes wished to improve in their current footwear options. The following characteristics were the top 4 characteristics as ranked by participants: arch support, breathability, ankle support, and weight. Responses to these four characteristics arose from both populations, showing that neither population strongly influenced the results in either question. Follow up discussions published by footwear manufacturers outline that athletes in older populations look for qualities such as weight, ankle support, and greater widths to cater to foot problems as they age. This was not a significant factor for the purpose of this study, and preferred footwear characteristics were comparable in both populations.

Finally, another significant question in the second section of this survey asked athletes to identify the region on their tennis shoes that displayed the most wear. The purpose of this question was to gain initial feedback on common regions of extreme wear and compare these to supplemental images provided in follow up analyses. With these regions identified early on, this would shape further data processing. Results of the responses provided in the survey are shown below in *Figure 9*.

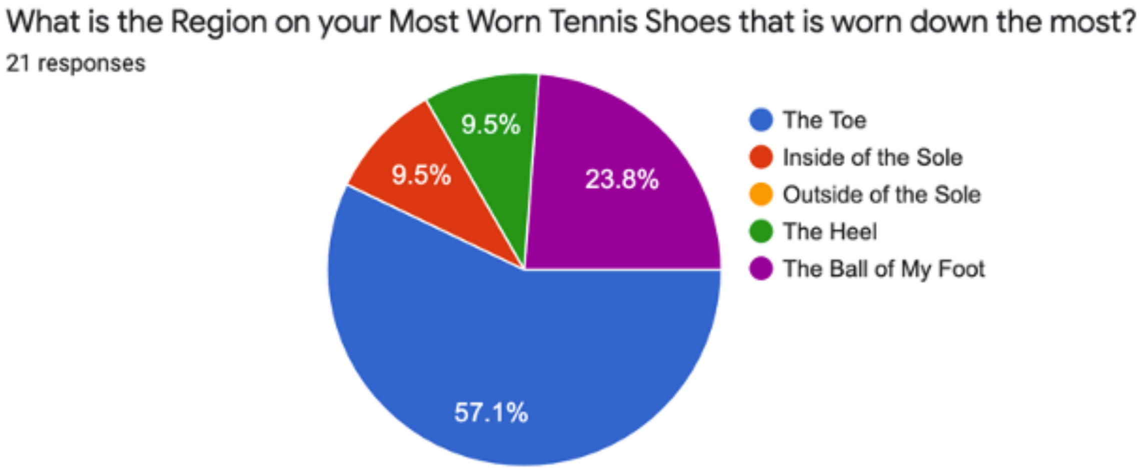

Figure 9. Identified regions of extreme wear on tennis footwear outsoles by participants. The most identified region was the toe, throughout both populations. This phenomenon was to be expected as many quick movements in tennis center on this portion of the foot. No pronation or supination effects were considered at this point in the research assessment.

Similar to phenomenons witnessed when conducting running footwear analyses, common regions of extreme wear occur at the forefoot on footwear outsoles. When changing lower body position or direction, this region experiences the greatest amount of contact time with the court surface. Acceleration and deceleration also exert great amounts of force on this region, therefore, resulting in instances of increased wear. While these results matched the initial hypothesis of the study stating that as athletes gain familiarity playing tennis and their competitive level of gameplay increases, wear patterns will begin to develop more quickly, there were effects at play[8]. Due to the nature of the question, athletes were not able to select if pronation or supination effects occur within their footwear wear patterns. These effects can lead to decreased product lifetimes and greater likelihood to sustain lower body injuries.

Section 3 – Previous Injury History

In the final section of this initial survey, participants were asked to identify their most recent injuries sustained while playing tennis or another sport. With similar athlete populations representing similar demographic factors and tendencies, this section was introduced in attempt to construct linkages between footwear wear patterns and common injuries that occur during sport. When participants were asked to recall their most recent injury sustained while playing tennis or other sports, the following responses were provided (*Figure 10*).

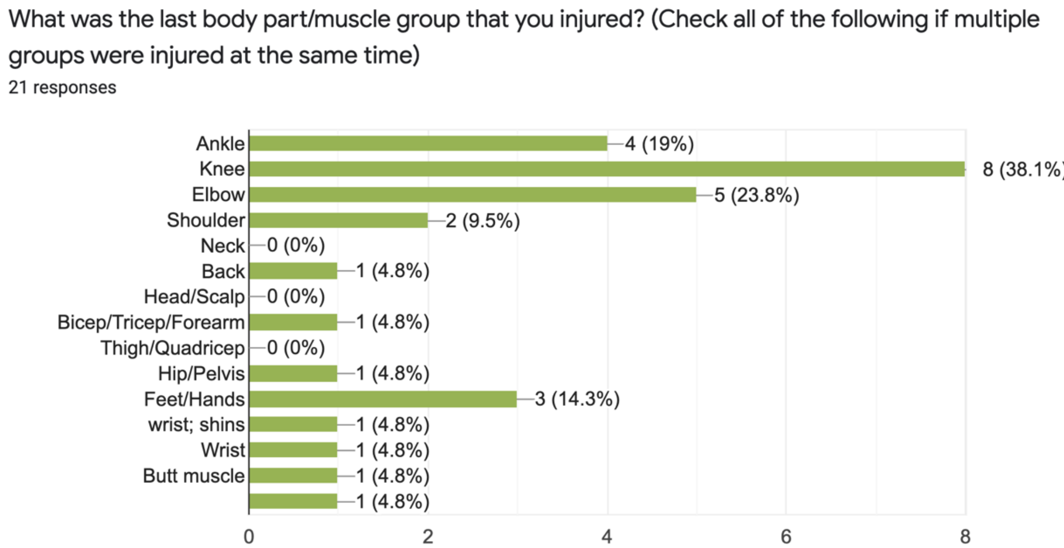

Figure 10. Responses of the most frequent injury occurring from each of the 21 participants in both populations. Lower body group and elbow injuries were the most common. These reported injuries match common injury trends for tennis athletes in various age groups and experience levels[7].

After conducting footwear imaging analysis, it became evident that those who had reported instances of extreme wear on the pronation region on the toe of the shoe were more likely to sustain injuries to the ankle or knee groups in the body. However, there was more variability among the young athlete population due to athlete recovery time, ongoing injury history, and more[7]. Because of these factors, populations reported different common injuries. Results by athlete population are shown below in *Figure 11*.

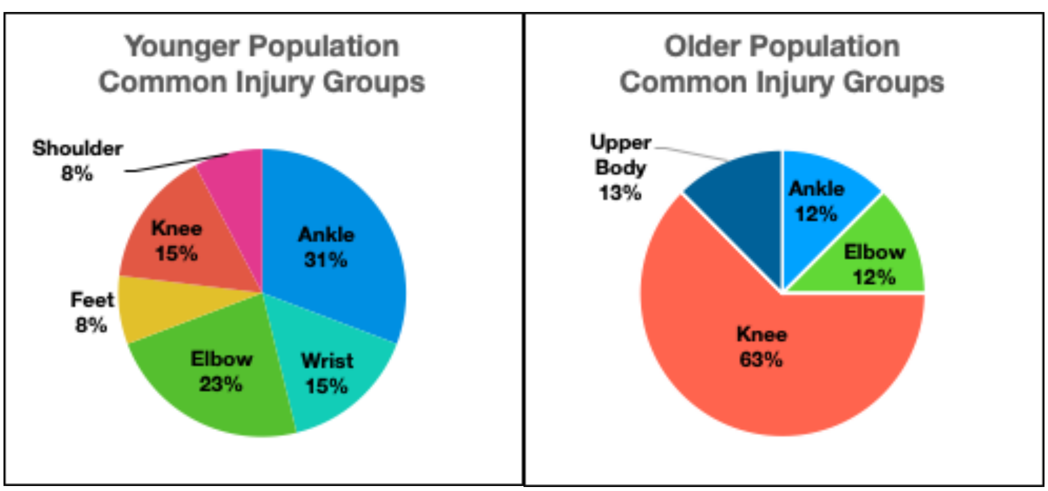

Figure 11. Overview of common injury groups in different tennis athlete populations. Injuries grouped by most common injury sustained while playing tennis.

Within the older athlete population, however, there was a much greater likelihood that athletes had been exposed to a recent lower body group injury (consisting of ankle, foot, knee, shin, quadricep, or pelvis). Effects from this population could be the result of a skewed (smaller) sample size, but follow other common injury reporting for tennis athletes over the age of 45. In order to combat these effects that older athletes might be subject to, there are footwear characteristics that can be sought out. A new technological advancement in footwear outsoles is introducing areas of greater outsole build-up. This allows athletes to find footwear options that offer thicker footwear outsoles in regions that undergo extreme wear faster than others. Footwear options within the product lines of Nike, Prince, Babolat, ASICS, and Adidas offer this feature. Lastly, different footwear construction geometries can be sought out in order to support characteristics of ankle support, breathability, arch support, and more. In today's game it is imperative that athletes seek out the options that support the longevity of their equipment and gameplay. In order to efficiently do this, equipment should be monitored and updated regularly to mitigate sustained injuries[9].

Footwear Image Analysis
With the results from sections two and three of the initial research survey, it was apparent that follow up analyses were necessary in order to accurately document pronation, supination, and extreme wear effects in footwear. Using the ranking scale and normalized wear average equation described above, the following worksheet was used to document and calculate normalized summary statistics of regions of extreme wear on footwear. Participants listed in *Table 1* below are participants that submitted images anonymously to be used for later analysis.

Table 1. Worksheet used to rank and calculate normalized extreme wear regions by athlete population. Summary statistics that were used in the MATLAB heatmap for each outsole region are listed below for each population.

Wear Rubric (Graded 1 - 3)										
All Participants (Young, Age < 26), (Older, Age > 26)										
			Toe		Upper Midsole		Lower Midsole		Heel	
Participant Number	Gender	Age	Pronation	Supination	Pronation	Supination	Pronation	Supination	Pronation	Supination
1	F	22	1	2	3	2	1	1	3	3
2	M	25	3	3	2	3	1	3	2	3
3	F		3	2	3	2	1	1	2	2
4	M	22	2	1	2	1	1	1	2	2
5	M	22	3	1	2	1	2	1	2	3
6	M	22	2	1	3	1	2	1	1	1
7	M	22	2	1	1	1	1	1	1	1
8	M	24	3	2	2	2	1	1	1	2
9	F	69	3	3	2	3	1	2	2	3
10	M	32	3	2	2	1	1	2	1	2
11	F	58	1	2	2	3	1	1	2	3
12	F	72	3	2	2	1	1	1	1	1
13	M	75	3	2	3	2	1	2	1	2
14	M	58	2	2	2	3	1	2	1	2
	Young Athlete Summary Statistics		Toe		Upper Midsole		Lower Midsole		Heel	
			Pronation	Supination	Pronation	Supination	Pronation	Supination	Pronation	Supination
			79	54	75	54	42	42	58	71
	Older Athlete Summary Statistics		Toe		Upper Midsole		Lower Midsole		Heel	
			Pronation	Supination	Pronation	Supination	Pronation	Supination	Pronation	Supination
			83	72	72	72	33	56	44	72

After these data points were collected through submitted participant images, the summary statistic values by outsole region were used to construct a heatmap of regions of extreme wear along the lateral profile of tennis footwear. The script that was used to generate this heatmap is listed below in *Appendix E*. The results from this heatmap are shown below in *Figure 12*.

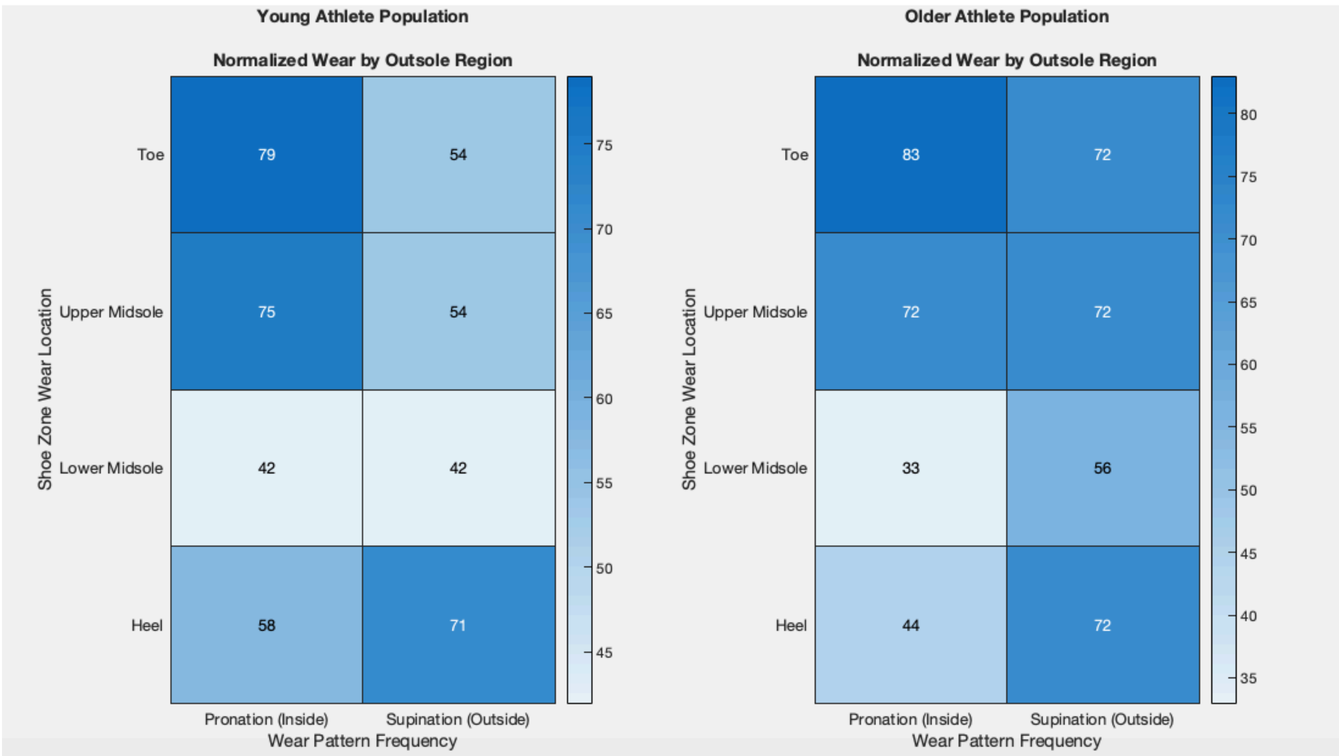

Figure 12. Normalized wear heatmap by regions of extreme wear. Regions on the left-hand side of the figure represent the inside of tennis footwear, correlating to pronation effects, and the right-hand side represents the outside correlating to supination effects.

The figure above is meant to depict the underside of the athlete's left shoe. In other words, the figure is oriented so that the toe of footwear is pointing up and the bottom of the shoe is coming out of the page. Results upon construction of this heatmap mirrored projected results from this research study. Both populations of athletes depicted extreme wear in both toe pronation and heel supination regions. This is likely the result of athletes changing direction and decelerating rapidly during gameplay. Other notable factors that arose from this image analysis show that athletes in the older population show extreme wear throughout the entire forefoot section, showing that the gait that they use while playing is different than young athletes or they continue to use footwear products under greater wear conditions than younger athletes. In order to better model how athletes from both populations prepare their footwork for shot preparation a follow-up biomechanical assessment was conducted.

Biomechanical Assessment and Motion Capture

In order to properly characterize footwork and footwear wear patterns during shot preparation for common tennis groundstrokes, 5 participants from the initial research study that submitted photographs for imaging analysis were asked to hit these shots while being documented by a slow motion capture camera. The objectives of this portion of the research project were to observe how athletes adjust their feet, if the observed footwear wear regions were justified during strokes, and if wear regions were impacted by the result of groundstroke continuation. Shot selection for each of these groundstrokes is previously listed in *Figure 2* above. Results from each of these shots are shown below in *Figures 13 – 14*.

Figure 13. Comparison of shot preparation for a common baseline groundstroke in both young (top) and older (bottom) athlete populations. The stroke hit in this example was a right-handed backhand (Stroke #4), and each snapshot occurs at the point of contact.

In this example of one athlete from each population hitting a common groundstroke, there are visible factors that correlate to the obtained results of extreme wear patterns in types of footwear. The athlete from the young athlete population displays toe pronation effects in their trail (left) foot and both pronation and supination effects in the toe and upper midsole region of their lead foot. This matches the level of wear characterized by the heatmap above. Similarly, the athlete from the older population displays pronation effects on their trail (left) foot, but displays heel supination effects as well. This trend also matches the heatmap, and greater wear on the shoe's lower midsole region is visible as the athlete advances through their shot. After confirming these effects in common groundstrokes, athletes were asked to hit an overhead serve (Stroke #5).

Figure 14. Comparison of shot preparation for an overhead serve (Stroke #5) between a participant from the young (top) and older (bottom) athlete population. Both images were taken at the apex of the stroke while the participant maintained contact with the court surface.

While many elements between both athletes in their footwork preparation to hit this stroke are very similar, there are factors that differ. For example, in the image at the top of *Figure 14*, the athlete from the young population exhibits extreme wear throughout the entire toe box but displays both pronation and supination effects on both feet. The athlete exhibits the most force on the toe region of the footwear throughout the length of the stroke. The lower image depicting the athlete from the older population hitting this groundstroke shows factors that also match results presented by the heatmap. This athlete's preparation indicates both pronation and supination in both feet, leading to greater weight transfer and distributed wear during the extent of the groundstroke. The results from these groundstrokes indicate that athletes exerting large amounts of force during these strokes produce great amounts of wear on footwear by representative regions. These shots accurately model this phenomenon and further research should be conducted in order to gauge relative wear by various gameplay styles.

Conclusions

In conclusion, the relationship between tennis athletes and their footwear wear patterns is an ever-changing dichotomy that continues to require further research to deliver innovative products. Both athletes and footwear manufacturers can take action in order to identify the proper characteristics in footwear. With increases in the number of data-driven technologies offered within the footwear industry, these technologies can be adapted to better serve the populations of tennis and racquet sport athletes for generations to come. For athletes in aging populations, there are measures that manufacturers can take in order to cater to the various needs of different styles of gameplay. These factors can include introducing products that offer greater accessibility, lower product cost, and better sustainability practices to extend product lifetimes.

From a player perspective, there a number of things athletes can do in order to promote the longevity and efficiency of their game. Regular maintenance of sporting equipment should be followed in order to protect athletes from injury, extreme cases of wear, and increase performance. When identifying characteristics that athletes enjoy in their footwear products, they should seek these out consistently. If financially able to do so, they should buy multiple pairs of shoes that feel comfortable and service the needs of their game. Regular cleaning of the outsole, upper, and insole can also extend the product lifetime of footwear products[10]. Ultimately, however, it is the responsibility of the athlete to monitor the wear on their footwear products. By carefully monitoring wear patterns of footwear and obtaining new products, this lowers the risk of injury.

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I would like to thank my mentor Dr. Ben Mason for stepping into a leadership role and guiding me during my final term in the Honors College. He has made time for countless appointments and acted as a great mentor moving forward in my professional career. Next, I would like to thank my committee members Dr. Benita Blessing and Dr. Eric Hill for their support as professors and mentors in coursework, and this writing process. Both have countlessly supported me in many academic and professional projects, and have stepped into prominent roles when I needed them to. I would also like to thank Beau Baca and the Honors College advising staff for their continued support in working to identify project mentors for students like myself during my time at Oregon State University.

I would also like to thank all those that participated in this study and provided responses, photographs, and/or permission to use video materials for the preparation of this thesis. Without your effort and support, this would not have been possible. Finally, I would like to thank my parents and brother for their continued support, motivating enthusiasm, and great humor throughout this data collection and writing process. Without the three of them, this would not have been possible.

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Appendices

Appendix A. Equations

Equation 1. *Normalized Average of Extreme Wear Conditions by Outsole Region*

$$WA_{i.outsole} = \left(\frac{\sum_{i=1}^{n} X_i}{3n}\right)(100)$$

**Where:*

WA_i represents the extreme wear conditions score for each outsole region.

X_i represents the individual outsole region wear score on each provided image on a 1 – 3 scale.

n represents the number of responses in each athlete population.

Appendix B. Figures

Thank you for submitting a response! If you feel comfortable please submit a picture of the bottom of your current tennis footwear resembling the picture above to (707)954-7728 or westbroa@oregonstate.edu to be later used in imaging analysis. Thank you!

Figure 1. Overview of response provided to participants that completed the survey.

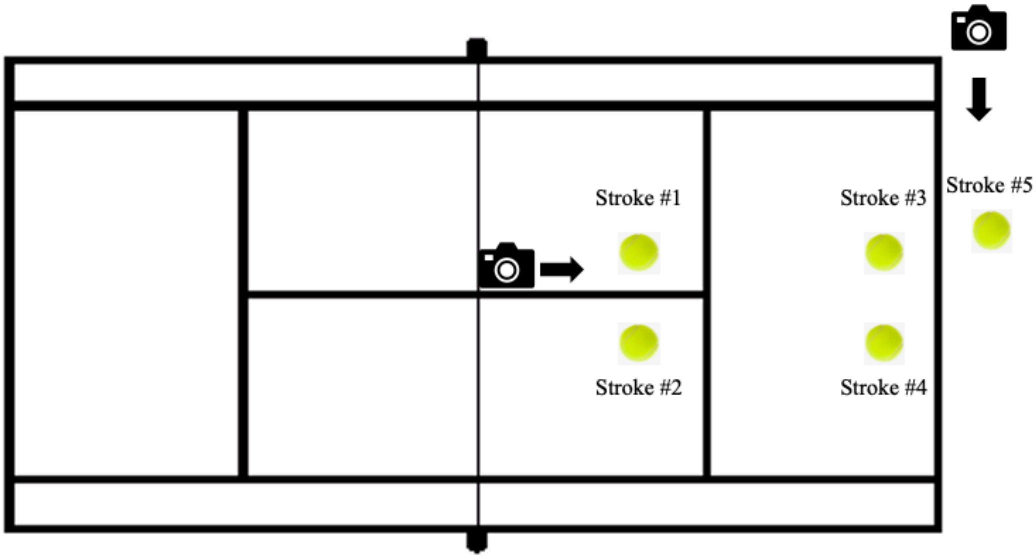


Figure 2. Overview of tennis court layout, camera location, camera shot angles, and locations of common groundstrokes. Athletes were asked to prepare for each of these shots as they normally would during their identified style of gameplay. For Stroke #5, the camera was moved perpendicular to athletes hitting their serve in order to fully account for foot placement and preparation for each shot.

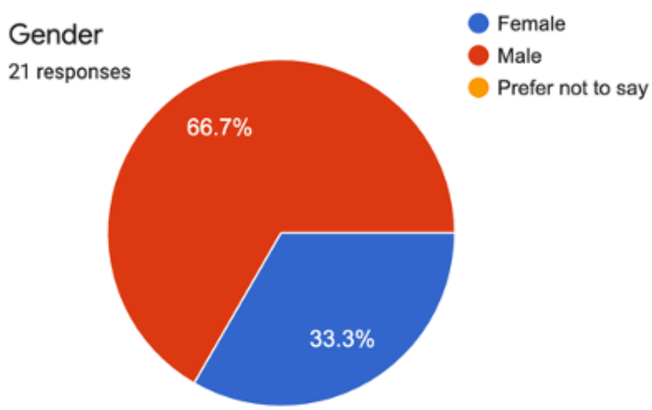


Figure 3. Breakdown of participants by gender. Of the 21 total participants from both populations that submitted responses to this initial survey, 14 were female and 7 were male.

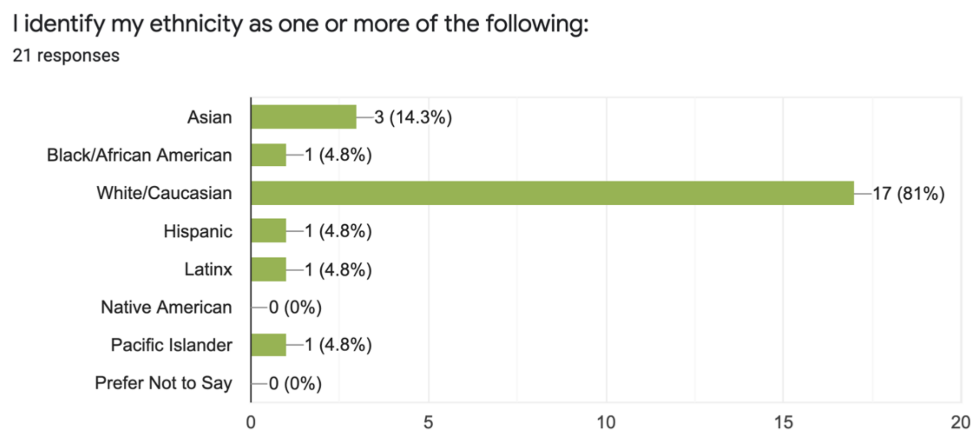


Figure 4. Breakdown of participants' identification of their associated ethnicity(/ies) based on common identifying factors. Each of these associated ethnicity identification options was chosen in order to comply with regulations set in place from other surveys that did not require IRB approval.

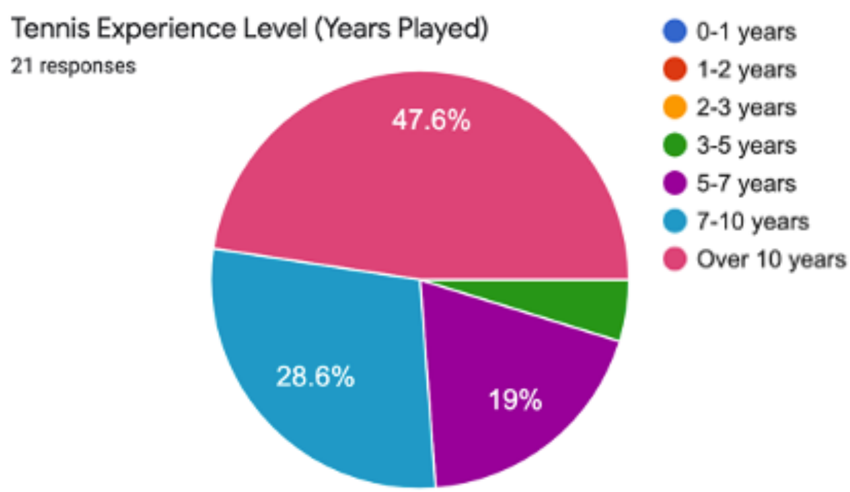


Figure 5. Composition of tennis athlete experience level by number of years played. While most of the older athlete population was composed of athletes that had played tennis for over 10 years, there were similar distributions of experience level in both populations. This demographic factor impacted both populations' relative wear patterns due to more efficient footwork with greater comfortability with the sport.

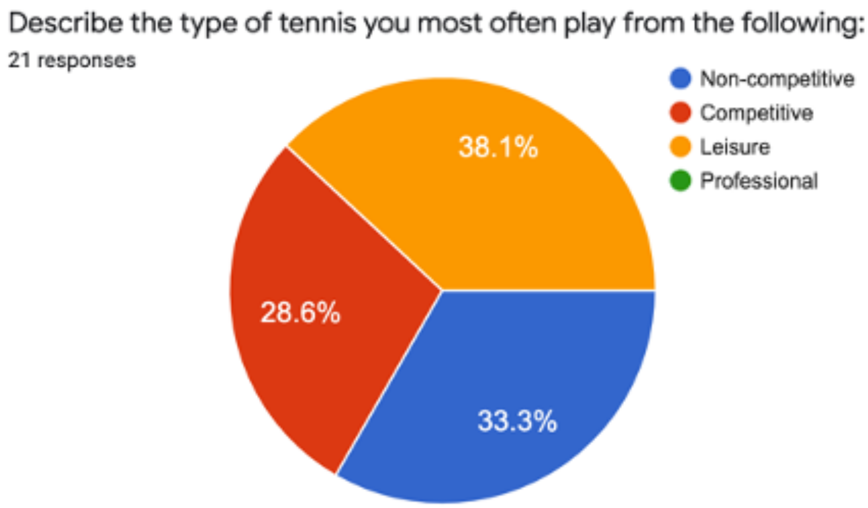


Figure 6. Results from the question asking participants to rate the level of competition that they engage in when playing tennis. Of the 21 participants, 8 designated that their most frequent style of gameplay is leisure. This term was to emulate styles of play normally characterized by participating in drills and improving skills. This term was intentionally left vague in order to have participants choose to characterize their style of play in a particular fashion.

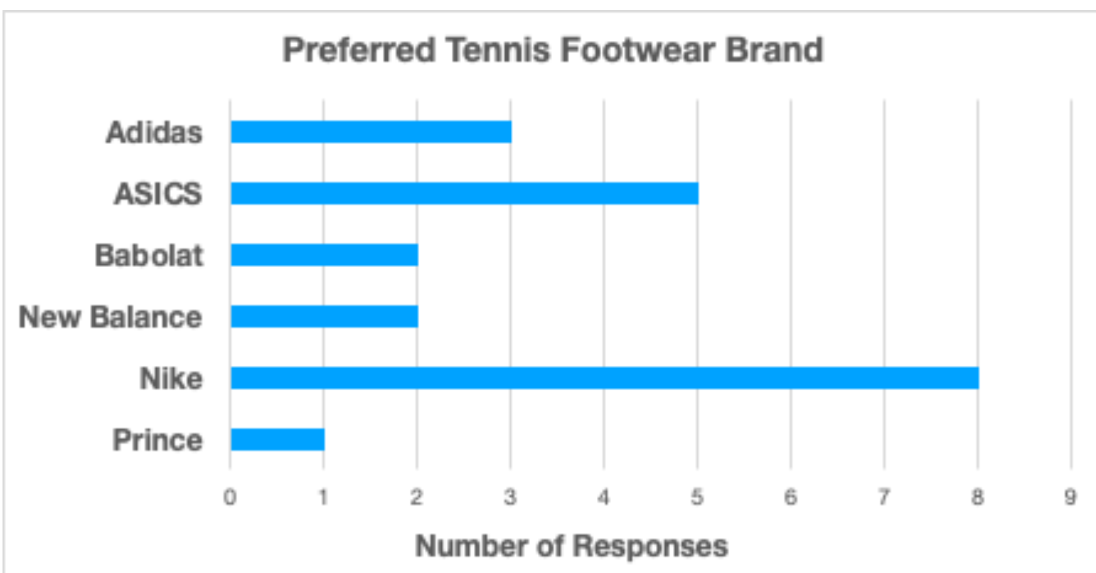


Figure 7. Results of athletes' preferred tennis footwear brands by number of responses. Nike was the most popular footwear manufacturer according to responses from this question. An important note for athletes in both populations is that Adidas, Nike, New Balance, Babolat, and Prince offer both wide and narrow widths for athletes with arch support needs or problems.

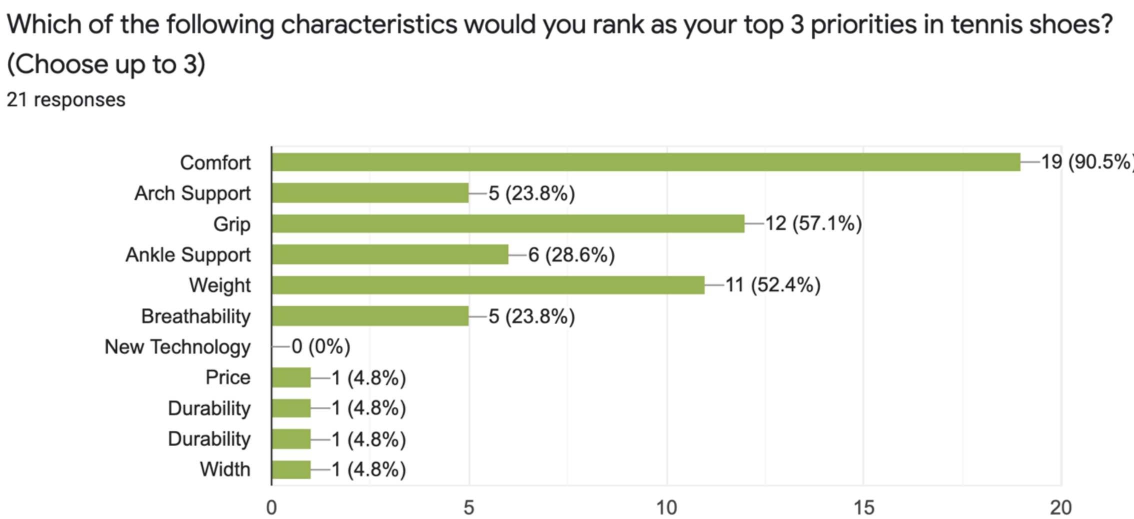


Figure 8. Results from the top 3 priority characteristics in tennis footwear elected by participants in this survey. Of the 21 participants that completed the initial survey, 19 indicated that comfort was a top priority. Second most behind comfort was grip, which can be directly linked to tennis footwear wear patterns sustained by athletes.

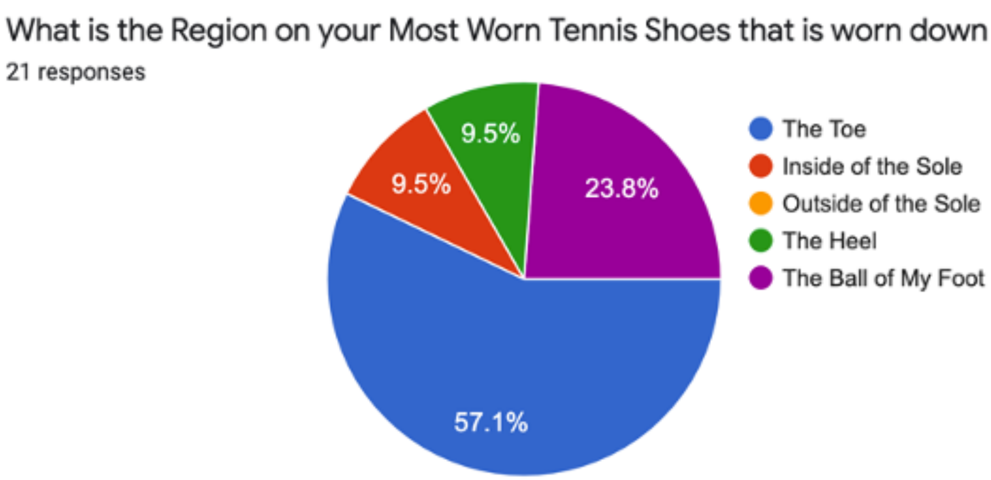


Figure 9. Identified regions of extreme wear on tennis footwear outsoles by participants. The most identified region was the toe, throughout both populations. This phenomenon was to be expected as many quick movements in tennis center on this portion of the foot. No pronation or supination effects were considered at this point in the research assessment.

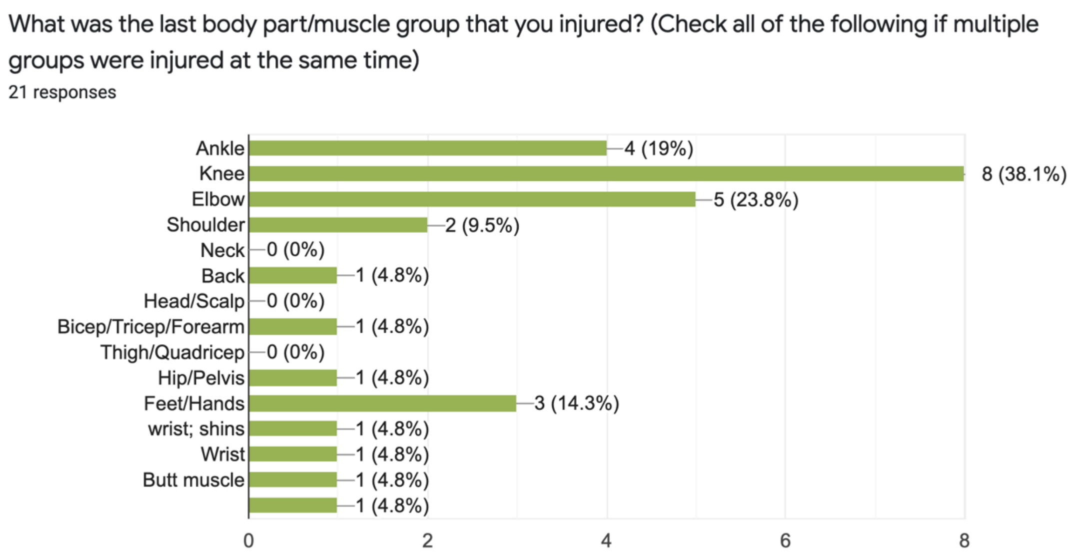


Figure 10. Responses of the most frequent injury occurring from each of the 21 participants in both populations. Lower body group and elbow injuries were the most common. These reported injuries match common injury trends for tennis athletes in various age groups and experience levels[7].

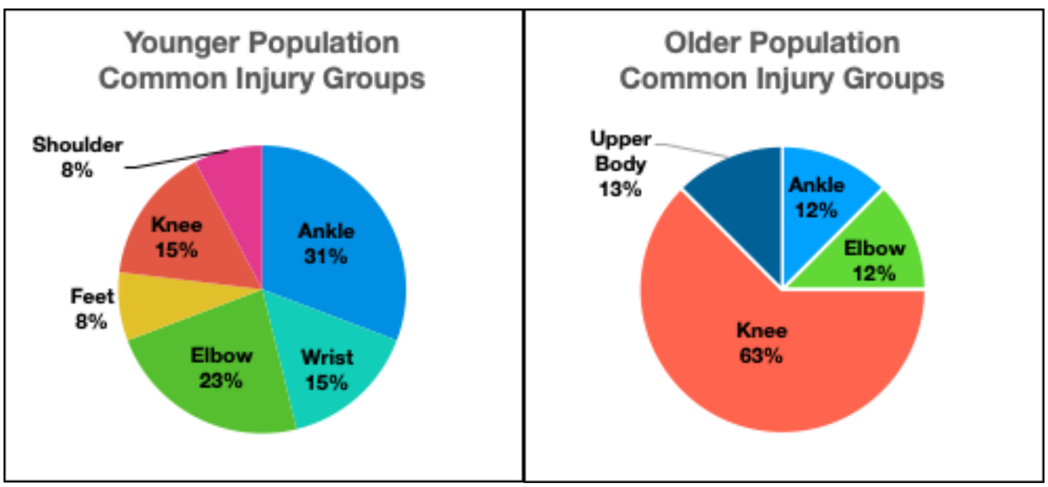


Figure 11. Overview of common injury groups in different tennis athlete populations. Injuries grouped by most common injury sustained while playing tennis.

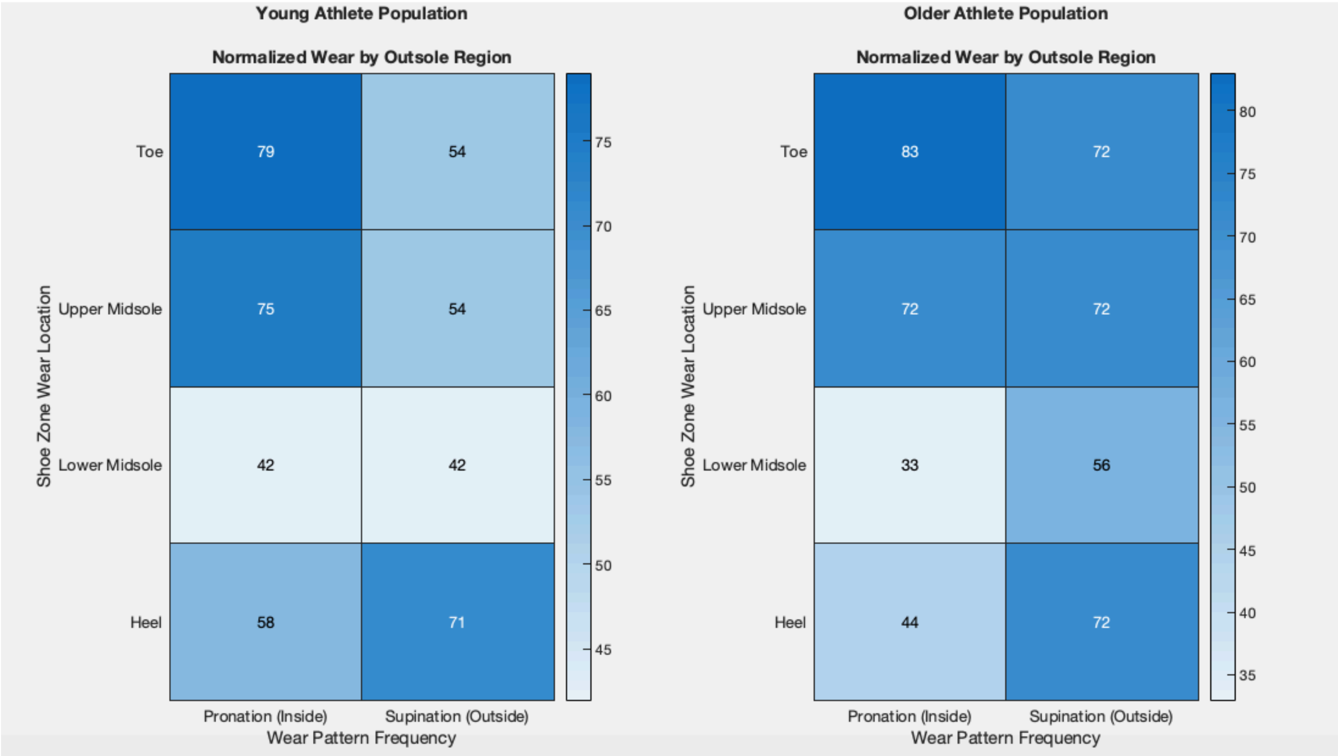


Figure 12. Normalized wear heatmap by regions of extreme wear. Regions on the left-hand side of the figure represent the inside of tennis footwear, correlating to pronation effects, and the right-hand side represents the outside correlating to supination effects.

Figure 13. Comparison of shot preparation for a common baseline groundstroke in both young (top) and older (bottom) athlete populations. The stroke hit in this example was a right-handed backhand (Stroke #4), and each snapshot occurs at the point of contact.

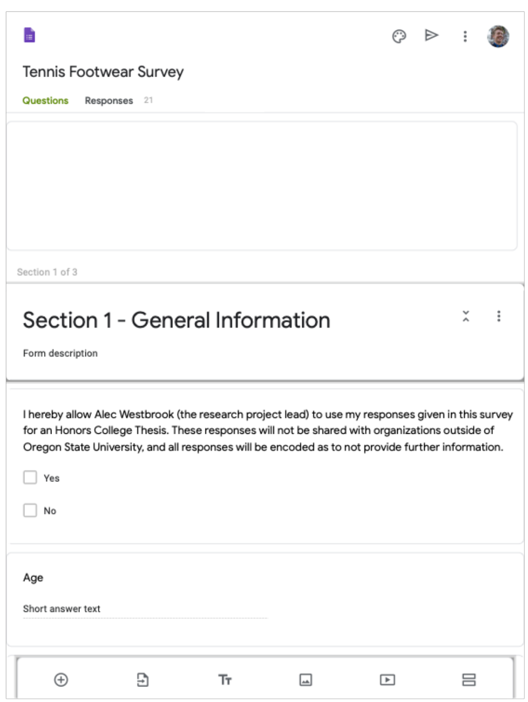
Figure 14. Comparison of shot preparation for an overhead serve (Stroke #5) between a participant from the young (top) and older (bottom) athlete population. Both images were taken at the apex of the stroke while the participant maintained contact with the court surface.

Appendix C. Tables

Table 1. Worksheet used to rank and calculate normalized extreme wear regions by athlete population. Summary statistics that were used in the MATLAB heatmap for each outsole region are listed below for each population.

Wear Rubric (Graded 1 - 3)										
All Participants (Young, Age < 26), (Older, Age > 26)										
			Toe		Upper Midsole		Lower Midsole		Heel	
Participant Number	Gender	Age	Pronation	Supination	Pronation	Supination	Pronation	Supination	Pronation	Supination
1	F	22	1	2	3	2	1	1	3	3
2	M	25	3	3	2	3	1	3	2	3
3	F		3	2	3	2	1	1	2	2
4	M	22	2	1	2	1	1	1	2	2
5	M	22	3	1	2	1	2	1	2	3
6	M	22	2	1	3	1	2	1	1	1
7	M	22	2	1	1	1	1	1	1	1
8	M	24	3	2	2	2	1	1	1	2
9	F	69	3	3	2	3	1	2	2	3
10	M	32	3	2	2	1	1	2	1	2
11	F	58	1	2	2	3	1	1	2	3
12	F	72	3	2	2	1	1	1	1	1
13	M	75	3	2	3	2	1	2	1	2
14	M	58	2	2	2	3	1	2	1	2
	Young Athlete Summary Statistics		Toe		Upper Midsole		Lower Midsole		Heel	
			Pronation	Supination	Pronation	Supination	Pronation	Supination	Pronation	Supination
			79	54	75	54	42	42	58	71
	Older Athlete Summary Statistics		Toe		Upper Midsole		Lower Midsole		Heel	
			Pronation	Supination	Pronation	Supination	Pronation	Supination	Pronation	Supination
			83	72	72	72	33	56	44	72

Appendix D. Initial Footwear Google Form Survey - Link to Survey


Tennis Footwear Survey
Questions Responses 21
Section 1 of 3
Section 1 - General Information
Form description
I hereby allow Alec Westbrook (the research project lead) to use my responses given in this survey for an Honors College Thesis. These responses will not be shared with organizations outside of Oregon State University, and all responses will be encoded as to not provide further information.
Yes
No
Age
Short answer text

Appendix E. MATLAB Script Used to Produce Wear Pattern Heatmap

```
%% Alec Westbrook - HC Thesis Survey Heatmaps
%% Background Information
% Wear patterns are split by two athlete populations
    % Younger Athlete Population Ages < 26
    % Older Athlete Population Ages > 26

% Use the following script to draw a heat map of common wear
patterns in
% shoe sole populations of different athletes in this study.

% Data is pulled from Excel workbook analyzing wear of athlete's
footwear

%% Young Athlete Population Data (Ages < 26)
%Below is normalized wear pattern data from images from the young
athlete
%population grouped into 4 footwear regions: toe, upper midsole,
lower
%midsole, and heel.
close all; clc

y_toe = [79 54];
y_uppermidsole = [75 54];
y_lowermidsole = [42 42];
y_heel = [58 71];

%% Older Athlete Population Data (Ages > 26)
%Below is normalized wear pattern data from images from the older
athlete
%population grouped into 4 footwear regions: toe, upper midsole,
lower
%midsole, and heel.

o_toe = [83 72];
o_uppermidsole = [72 72];
o_lowermidsole = [33 56];
o_heel = [44 72];

%% Plot Figure - Common Wear Patterns by Athlete Population

%Plotting Information

%new figure for both heatmaps plotted
figure('Name','Common Wear Patterns by Athlete Population',...
    'NumberTitle','off','rend','painters','pos', [150 150 1200
650]);

%create younger population heatmap
hold all
title('Wear Patterns by Athlete Population')
subplot(1,2,1)
cdata = [y_toe; y_uppermidsole; y_lowermidsole; y_heel];
```

```
xvalues = {'Pronation (Inside)','Supination (Outside)'};
yvalues = {'Toe','Upper Midsole','Lower Midsole','Heel'};
h = heatmap(xvalues,yvalues,cdata);
h.Title = {'Young Athlete Population',' ', ...
    'Normalized Wear by Outsole Region'};
h.XLabel = 'Wear Pattern Frequency';
h.YLabel = 'Shoe Zone Wear Location';
h.FontSize = 13;

% create second heatmap of older adult population
subplot(1,2,2)
bdata = [o_toe; o_uppermidsole; o_lowermidsole; o_heel];
xvalues1 = {'Pronation (Inside)','Supination (Outside)'};
yvalues1 = {'Toe','Upper Midsole','Lower Midsole','Heel'};
g = heatmap(xvalues1,yvalues1,bdata);
g.Title = {'Older Athlete Population',' ', ...
    'Normalized Wear by Outsole Region'};
g.XLabel = 'Wear Pattern Frequency';
g.YLabel = 'Shoe Zone Wear Location';
g.FontSize = 13;
```

Appendix F – Submitted Participant Footwear Images

Participant Number	Submitted Image
1	

2	
3	
4	

5	
6	
7	

8			
9			
10			

11			
12			
13			

14