Leveraging Additive Manufacturing and Engineering Design Methods to Improve Ballet Pointe Shoes

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ABSTRACT

Pointe shoes allow a dancer to create the aesthetic of effortless movement. The materials used to make pointe shoes are composed of leather, glue-hardened burlap, satin, and fabric-materials that deteriorate quickly. With current research efforts surrounding the biomechanics when a dancer is on pointe, there is a huge gap in research around implementing new methods of manufacture, such as Additive Manufacturing, that may increase the quality and robustness of shoes. Comparatively, within the sports performance industry, leading companies have already applied Additive Manufacturing (AM) techniques to fabricate innovative footwear. This work explores the implementation of AM for the application in pointe shoes. By studying professional dancers’ experiences, the insights drove the design phase to focus on creating a pointe shoe shank using AM primarily. The design iterations were created through Finite Element Analysis (FEA) and compliant mechanism design to deliver similar characteristics to a standard shank. Furthermore, this work also examined designing the entire pointe shoe using AM. These results suggest the significant potential of implementing AM methods to improve pointe shoes and fill the significant gap currently experienced in the ballet field.
# TABLE OF CONTENTS

LIST OF FIGURES ......................................................................................... iii

LIST OF TABLES ........................................................................................... iv

ACKNOWLEDGEMENTS .............................................................................. v

Chapter 1 Introduction ............................................................................... 1

Chapter 2 Background ............................................................................... 5

  2.1 Pointe Shoe Fundamentals ................................................................. 5
  2.2 Analysis of Pointe Shoe Biomechanics ............................................... 6
  2.3 Design Efforts in Pointe Shoes .......................................................... 11
  2.4 Human-Centered Design Methodologies ......................................... 12
  2.5 Additive Manufacturing Techniques .............................................. 14
  2.6 Mechanical Design Methods ............................................................ 17
  2.7 Research Questions .......................................................................... 18

Chapter 3 Understanding User Needs ....................................................... 21

  3.1 Design of Study ............................................................................... 21
  3.2 Participants ...................................................................................... 24
  3.3 Data Analysis ................................................................................... 24
  3.4 Personal Interviews .......................................................................... 35

Chapter 4 Design of Pointe Shoes via Additive Manufacturing .................... 38

  4.1 Validation of Compliant Mechanisms ............................................. 38
  4.2 Prototyping Process of a Full Pointe Shoe ....................................... 47

Chapter 5 Conclusion ................................................................................. 51

Chapter 6 Limitations and Future Work .................................................... 53

Appendix A Survey of Professional Dancers ........................................... 55

Appendix B Email Distributed to Participants ......................................... 60

BIBLIOGRAPHY ......................................................................................... 61


LIST OF FIGURES

Figure 1. Traditional pointe shoe materials (Kumar, 2013) .................................................. 3
Figure 2. Pointe shoe anatomy (Stefi, 2020) ........................................................................... 3
Figure 3. Supplies used to prepare pointe shoes (Smith, 2014) ................................................ 6
Figure 4. Nike Flyprint process of the upper (Nike, 2018) .......................................................... 7
Figure 5. 'Dead' pointe shoes that are worn for many hours, resulting in reduced support in the
shank and box area (Partoon, 2015) ......................................................................................... 8
Figure 6. Neutral position identified as ATFL- anterior talofibular ligament (Russell et al., 2008) 9
Figure 7. Plantar flexion where the toes are pointed away from the body (Kanthi, Mruthyunjaya,
& George, 2013) ..................................................................................................................... 9
Figure 8. Human-Centered Design Process (DC Design, 2019) .................................................. 12
Figure 9. FDM Process (Mohamed, 2016) ................................................................................ 14
Figure 10. Pointe shoe brands (Cunningham et al., 1998) ......................................................... 15
Figure 11. Cobbler making shoes (Weber, 2015) ....................................................................... 16
Figure 12. 3D-printed bistable arch (Palathingal & Ananthasuresh, 2017) ......................... 18
Figure 13. Treemap of prevalent problems ............................................................................... 25
Figure 14. Link analysis of responses ......................................................................................... 26
Figure 15. Packed bubble chart of protection materials dancers used .................................... 27
Figure 16. Diagram of locations where discomfort is experienced ............................................. 31
Figure 17. Deconstructed pointe shoe (Sullivan, 2015) ............................................................ 39
Figure 18. Iteration 1 of 3D pointe shoe shank ......................................................................... 40
Figure 19. FEA analysis of case study 1 ...................................................................................... 41
Figure 20. Iteration 2 of 3D pointe shoe shank ......................................................................... 42
Figure 21. FEA analysis of case study 2 ..................................................................................... 43
Figure 22. Iteration 3 of 3D pointe shoe shank ......................................................................... 44
Figure 23. FEA analysis of case study 3 ..................................................................................... 45
Figure 24. Topology optimization of a basic shank and box model (front view).................... 47
Figure 25. Topology optimization of a basic shank and box model (side view).................... 48
Figure 26. Design process for an entire pointe shoe......................................................... 50
LIST OF TABLES

Table 1. Research Methodology .................................................................................. 23
Table 2. Spearman’s rho correlation between features of pointe shoes ......................... 29
Table 3. Multinomial logistic regression significance values (area vs. brand) ................. 30
Table 4. Multinomial logistic regression significance values (discomfort area vs. brand) .... 31
Table 5. Chi-Squared test between the pointe shoe brand and bucketed injuries ............ 32
Table 6. ANOVA test between brand and number of hours danced per week ................. 33
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Chapter 1

Introduction

Pointe shoes are foundational to a ballerina’s craft and create an illusion of lightness and the appearance that the ballerina is floating on air (Guiheen, 2020). The visual effects of pointe shoes are numerous; elongation of the limbs and rapid, continuous pirouettes (a complete turn on the toe or ball of one foot). In the early 1830s, an Italian ballerina named Maria Taglioni was the first ballerina to dance on her toes and break all previous barriers in ballet (Pittsburg Ballet Theatre, 2020). While the shoes were modified satin slippers made of leather, it eventually led to the span of modern pointe shoes, with early 20th-century Russian ballerina Anna Pavlova pioneering the movement (Guiheen, 2020). Pointe dancing continues to evolve as artistic expression transforms through new styles; however, little work has investigated designing the pointe shoe with new manufacturing methods such as Additive Manufacturing (AM) for increased durability, comfort, and support.

In looking at other athletic activities, there is significant support and evidence of how footwear innovation has transformed the sports performance industry. Eliud Kipchoge, a marathon world-record holder, recently became the first person to complete a marathon in Vienna in under two hours (Burgess, 2019). Kipchoge wore the Nike Air Zoom AlphaFly Next% shoes, which contained a single carbon fiber plate, ZoomX cushioning, and a knitted material called Atomknit – the best combination of materials to decrease lost energy and increase efficiency (Burgess, 2019). Similarly, a study that tested newly developed running shoes to established marathon shoes found an average reduction of 4% in the energetic cost of running in the newly developed shoes.
The prototype shoes were designed by Nike and included extensive cushioning and light materials. These innovations highlight the vast amount of innovation in running footwear and how materials and construction play a significant role in performance. In 2018, Adidas partnered with a start-up in Silicon Valley called Carbon to make 3D printed shoes a reality (Carlota, 2018). Following the partnership, the Futurecraft 4D was later released, a performance shoe that utilized a 3D-printed resin process to create a midsole with varying lattice structures and significantly reduced raw material and environmental costs (Scholkowski, 2017). This process involved creating the midsole layer-by-layer using liquid polymer to obtain the desired specifications of an athlete. Additive manufacturing enables the development of advanced footwear through faster prototype development, personalization, and testing. Sports footwear companies have adopted AM because of the practical benefits of meeting ever-evolving consumer demand (Manoharan, Chou, Forrester, Chai, & Kong, 2013).

Today’s ballet pointe shoes give a beautiful aesthetic on the outside, but the interior lacks innovation and, in essence, has remained the same for roughly 200 years. The materials in pointe shoes include layers of packed fabric, cardboard, paper hardened by glue, leather, cotton, and satin (Pittsburgh Ballet Theatre, 2020). The layers of packed fabric are similar to paper mâché, where each layer is adhered to another using a glue paste. As shown in Figure 1, the materials in a pointe shoe are much different from those mentioned in Nike’s Air Zoom AlphaFly Next% and Adidas’s Futurecraft 4D shoe that utilized AM advancements and cushioning engineering. The sports footwear space has seen incredible innovation and benefits, having implemented AM techniques; however, pointe shoes have not experienced such adoption of AM methods. AM poses a unique opportunity for innovation of the ballet industry because it has the potential to save ballet companies hundreds of thousands of dollars each year, improve the comfort and function for
professional ballerinas, and yield flexibility in the design process- resulting in the personalization of footwear (Manoharan et al., 2013).

![Figure 1. Traditional pointe shoe materials (Kumar, 2013)](image1)

![Figure 2. Pointe shoe anatomy (Stefi, 2020)](image2)

The core components of a pointe shoe are the platform, box, and shank (Figure 2). The platform is the squared toe of the pointe shoe that enables a dancer to rise onto the toes (Bloch). The box is the hardened surface around the metatarsals that consist of the vamp, wings, and platform, which is bonded together in layers of fabric surrounding the foot’s front area (Bloch).
Lastly, the shank is a critical area inside the insole of a pointe shoe that supports a dancer’s arch and provides stability (Bloch). As a dancer works through their pointe shoes during rehearsals, the box begins to soften, and the shank loses its structural integrity to the point where the shoe becomes too soft, and a dancer must replace their shoes (Cunningham, DiStefano, Kirjanov, Levine, & Schon, 1998). In fact, pointe shoes deteriorate so frequently that experienced professional dancers wear 60 pointe shoes in a month and three pointe shoes in a single performance (Colucci & Klein, 2008; Cunningham et al., 1998). Due to the need to constantly replace shoes, ballet companies spend upwards of $100,000 on pointe shoes each year (Pittsburgh Ballet Theatre, 2020). Given these many limitations of pointe shoes regarding construction and cost, there are immense opportunities to disrupt the current pointe shoe industry with a new re-engineered design and mode of manufacture that utilizes the latest technology of Additive Manufacturing and cushioning innovation. Furthermore, since pointe shoes are made by hand with little automation, AM has the potential to significantly reduce the time to market for pointe shoes while precisely factoring in the unique specifications of each dancer.
Chapter 2

Background

The purpose of this work is to explore what engineering design techniques can be utilized to create a more innovative pointe shoe. Specifically, this research examines how engineering design techniques such as Additive Manufacturing may extend the lifetime and increase pointe shoes’ comfort and function. Similarly, an analysis of professional dancers and their issues with pointe shoes is also examined. However, before discussing the results, it is necessary to situate the research in the context of existing literature concerning pointe shoe fundamentals, biomechanics, current design efforts, human-centered design methodologies, additive manufacturing, and mechanical design methods.

2.1 Pointe Shoe Fundamentals

Pointe shoes are essential to the art of ballet and enable a ballerina to embody qualities of lightness and gracefulness through movement (Pittsburg Ballet Theatre, 2020). This career path is highly competitive and requires all energy invested in training and dancing (Hoogsteyns, 2013). With most professional dancers training six to seven hours a day, preparation of shoes is critical in a dancer’s daily routine (Rigby, 2012). Every dancer has a specific way to prepare their shoes. The typical steps include darning (using strong thread and needle to create a wider platform to balance) the platform of the box for increased durability, softening the box with a hammer, closing a door on the box, using shellac or super glue inside the shoe to prolong wear, and sewing on ribbons and elastic (Pittsburgh Ballet Theatre, 2020). As shown in Figure 3, dancers use various instruments to prepare their shoes and increase durability. With a professional ballerina’s intense
training schedule, one typically goes through 100-120 pairs of pointe shoes in one season (Pittsburgh Ballet Theatre, 2020). Thus, a dancer must always have a pair, prepped and ready-to-go for performances or rehearsals.

![Figure 3. Supplies used to prepare pointe shoes (Smith, 2014)](image)

### 2.2 Analysis of Pointe Shoe Biomechanics

The footwear industry has experienced immense innovation (Skillings, 2020); however, pointe shoes continue to have little support and shock absorption. For example, Nike created the first 3D printed textile upper (parts of the shoe located above the sole) that uses solid deposit modeling (SDM), in which thermoplastic polyurethane (TPU) is melted in layers. In particular, this method allowed for improved frictional resistance between interlaced layers of TPU, more breathability, and lightness (Nike, 2018). As shown in Figure 4, the SDM process allows for the unique creation of complex geometries.
On the other hand, pointe shoes are comprised of cardboard, fabric, satin, and leather. This simple comparison showcases the lack of research efforts in developing a better pointe shoe using AM methodologies that have improved life, comfort, and function.

Most dancers’ injuries are due to overuse in professional and amateur dancers (Smith et al., 2015). Injury prevention is essential to a professional dancer’s career, which may be influenced by creating a revolutionary shoe designed to mitigate the effects on the body. Whereas most published research articles focus on the lower extremities (ankle, knee, hip), this research proposes a sustainable injury incidence approach. In the study by Aquino, Amasay, Shapiro, Kuo, & Ambegaonkar (2019), dancers wearing ‘dead’ pointe shoes displayed increased swaying in relevé (when a dancer rises onto the tips of the toes) and arabesque (a pose where a dancer stands on one leg and extends the other leg in the air) positions, indicating increased effort when wearing ‘dead’ shoes. As shown in Figure 5, ‘dead’ pointe shoes can be identified by extensive wear in the shank, box and, overall decreased support.
Specifically, mid-foot flexion in a new pointe shoe in comparison to old pointe shoes was 89.5 ± 5.5° and 96.1 ± 3.9° respectively (Bickle, Deighan, & Theis, 2018). Worn pointe shoes have decreased support as the use increases. When considering performance and injury, wearing ‘dead’ pointe shoes reduces a dancer’s stability when performing movements and increases the likelihood of injury. Similarly, in a study comparing new pointe shoes to worn pointe shoes, Russel found more significant ankle flexion levels and mid-foot flexion in a worn pointe shoe, specifically in the shank section (2015). With professional dance companies reporting “67% - 95% of their dancers are injured on an annual basis,” there is an immense need to develop a pointe shoe with extended life and increased structural integrity (Gamboa, Robert, & Fergus, 2008).

As stated by the Atlanta Ballet, professional dancers typically train upwards of 8 hours a day (Atlanta Ballet). Therefore, a properly functioning ankle is critical to dance (Russell, McEwan,
Koutedakis, & Wyon, 2008). Figure 6 shows the area identified as the ATFL (anterior talofibular ligament), which is essential to allow one’s ankle to flex forward and backward. When performing pointe work, it is evident that strain in the anterior talofibular (a ligament in the ankle) increases with increasing plantarflexion or one’s ability to move their foot in a downward motion away from the body (Russel et al., 2008). Likewise, Figure 7 depicts plantar flexion movement, where the toes point away from the body compared to dorsiflexion, where the toes curl towards the body. Plantar flexion is crucial as it relates to ballet because its motion allows a ballerina to transition from a neutral foot position to rising onto the tips of the toes.

Figure 6. Neutral position identified as ATFL- anterior talofibular ligament (Russell et al., 2008)

Figure 7. Plantar flexion where the toes are pointed away from the body (Kanthi, Mruthyunjaya, & George, 2013)
In Russel’s analysis of the ankle’s biomechanics, the anterior talofibular is a weak ankle ligament and experiences maximum tension force on pointe (2008). By analyzing the maximum plantar flexion, pointe shoe designs can be refined to satisfy these requirements safely. In particular, Cunningham et al. (1998) found that the impact forces acted upon on a dancer landing from a 1 m height are 4950 N. By analyzing the axial loading of five different shoes from leading pointe shoemakers, Cunningham et al. concluded that the shoes compressive strengths were less than 4300 N (1998). Therefore, the pointe shoe toe box cannot withstand the impact forces from a jump, independent of the shoe type (Cunningham et al., 1998). In comparing flat ballet shoes to pointe shoes when a dancer performs a pirouette, pointe shoes cause increased ground reaction forces and increased movement of joints in the lower body—emphasizing the impact of footwear on various joints such as the hip, knee, and ankle (Mayumi & Yoshida, 2015). These dance studies highlight the biomechanics relevant to dancers’ use of pointe shoes. An important takeaway from pointe shoe biomechanics research is the impact of worn pointe shoes on increased ankle flexion that, over time, raises a dancer’s likelihood to develop a severe injury. Additionally, the forces experienced when on pointe influence a dancer’s ankle and other lower extremities. With the durability and support greatly lacking in pointe shoes, there is an opportunity to fill this gap with AM, a driver for increased comfort through customization and design possibilities (SmarTech, 2019).
2.3 Design Efforts in Pointe Shoes

Innovation in pointe shoes has largely been overlooked. There is a need for a novel design to greatly reduce injuries that, over time, if not addressed, can halt one’s ballet career indefinitely. In a study examining the injury rate among professional dancers for one year, it was found that “a mean of 6.8 injuries per dancer (females, 6.3; males, 7.3; p > .05) were recorded” (Allen, Nevill, Brooks, Koutedakis, & Wyon, 2012). The study emphasizes that there is a significant need to reduce the risk of injuries in professional dancers. By nature, pointe shoes are complex and must be strong enough to support a dancer’s arch while also being flexible enough to allow for a full range of motion in the foot and ankle.

A study conducted by Colucci & Klein (2008) examined the ergonomic and design factors of pointe shoes to prototype a new design. After interviewing 29 ballerinas, researchers found that durability, aesthetics of the shoe, and quietness are essential design characteristics (2008). Gaynor Minden is a pointe shoemaker company that promotes an unbreakable shank; however, this was not a quality that dancers desired in Colucci and Klein’s research. The pointe shoe shank supports a dancer’s arch, but it must have opposing properties—flexibility and strength (2008). The final prototype model implemented memory foam lining to reduce the noise (2008). While this research focuses on an innovative pointe shoe design, it does not explore the scope of additive manufacturing in ballet footwear. Surprisingly, the research by Colucci & Klein is the only study in the entire field that explores the development of a better pointe shoe. The lack of numerous research studies motivates innovation in the ballet space and highlights the opportunities to fabricate a more effective, durable model.
2.4 Human-Centered Design Methodologies

The human-centered design process is a fundamental structured approach for practical design. The principles of human-centered design focus on the end-user throughout the entire design process (Harte et al., 2017). Figure 8 displays the six steps of the human-centered design process that continue to influence designers’ approach to problem-solving and product development.

![Human-Centered Design Process](image)

**Figure 8. Human-Centered Design Process (DC Design, 2019)**

The first step involves understanding the experiences and perspectives of the end-user. Empathy is a critical aspect of the design process because “consumers’ perceptions of products strongly influence product’s acceptance” (Alcántara, Artacho, González, & García, 2005). The next step is defining user requirements based on the design objective (Harte et al., 2017). The ideation stage
involves generating ideas for how to address the specific problem mentioned by the user. Next, the prototyping stage involves developing high-fidelity or low-fidelity prototypes of the intended product (Harte et al., 2017). The fifth stage consists of testing the prototype to validate the initial assumptions and determine if it meets the user’s needs. Since the human-centered design process is continuous, iterate is the last step that identifies areas for further refinement and improvement.

As it relates to pointe shoes, the particular end-user investigated was professional dancers. This user has precise requirements and preferences for their pointe shoes. Following the human-centered design methodology and ensuring that the user was involved from the beginning of the research laid the foundation for future research avenues, particularly the exploration of additive manufacturing. One of the major benefits of AM is high design complexity and customization. For example, a Canadian start-up named FitMyFoot creates custom 3D-printed insoles from a customer’s foot measurements through their app. Their technology maps 200 points of each foot and generates a 3D-printable file specific to each foot (FitMyFoot).

With professional dancers having particular needs and preferences in how their pointe shoes feel and aesthetically look, customization from AM methods would significantly improve consistency from one pair to the next. Additionally, AM would allow for more durable materials such as Nylon and Carbon Fiber in critical components of pointe shoes like the shank and box. This would be a significant upgrade from the cardboard, burlap, and fabric materials currently used. Together through increased consistency of pointe shoes and implementation of durable materials, dancers may see reductions in the frequency of injuries in one’s ballet career.
2.5 Additive Manufacturing Techniques

Additive manufacturing is a method that builds an object layer-by-layer by blending materials either by fusion, binding, or solidifying materials (Abdulhameed, Al-Ahmari, Ameen, & Mian, 2019). Fused Deposition Modeling (FDM) is one AM process that uses layered manufacturing technology to extrude material through a nozzle, which is heated and melts the material (Abdulhameed et al., 2019). The nozzle translates in the x, y, and z-direction based on each layer’s tool path. Some common materials used to print objects are PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), PETG (Polyethylene terephthalate), and Nylon. As shown in Figure 9, there are various steps involved in FDM. The 3D CAD model is where a designer will create a 3D object and then convert the part file to an STL file, containing information about the part geometry (Abdulhameed et al., 2019). Slicing software is then used to convert the 3D object into instructions that the 3D printer can read. Typically, printing parameters are adjusted in the slicing software step, such as print speed, print temperature, supports, infill, and filament material. The final step involves printing the prototype on a 3D printer.

![Diagram of FDM Process](image)

Figure 9. FDM Process (Mohamed, 2016)
Additive manufacturing has exploded as a means to support the ever-evolving consumer demands and preferences in the sports footwear industry (Manoharan et al., 2013). In addition to faster prototyping than conventional manufacturing methods, AM techniques allow for personalization – a solution to improve fit, performance and reduce the likelihood of injury (Cheng & Perng, 1999; Sun, Chou, & Sue, 2009). Footwear companies such as Adidas, New Balance, and Wolverine frequently use 3D printing for prototyping because of the high performance of materials, higher printing speed, minimal waste, and various color options (Cheng & Perng, 1999; Sun et al., 2009). Among the following pointe shoe brands: Freed, Grishko, Bloch, Gaynor Minden, Capezio, Russian Pointe, and Suffolks, Gaynor Minden has the most innovation with the use of flexible polymers. However, no brands utilize 3D printing techniques in their models (Figure 10). The importance of flexible polymers in the Gaynor Minden shoe is increased flexibility, strength, and resilience in their pointe shoes (Gaynor Minden, 2017).

![Pointe shoe brands](image)

Figure 10. Pointe shoe brands (Cunningham et al., 1998)
With pointe shoemaking being a specialized craft that is physically intense for cobbler (individuals who make pointe shoes), there is a need to adopt new methods of manufacture. Shoemakers commonly die-cut the sole, followed by the toe box formation, where fabric and glue layers are added (Hilton, 2019). One standard manufacturing method used to make pointe shoes is called turn-shoe. The shoe is initially assembled inside out on a shoe last (3D plastic foot form mold upon which a shoe is constructed). It then is reversed to its final orientation during the last steps of the manufacturing process. Figure 11 captures a cobbler making pointe shoes by hand and shaping the platform.

Figure 11. Cobbler making shoes (Weber, 2015)

With every dancer having a unique foot morphology, consistency between pairs of pointe shoes is vital for comfort and injury prevention. Research conducted by Salles and Gyi (2012) investigated a footwear personalization method, consisting of “foot capture using a 3-D scanner, anthropometric measurements, insole design using CAD software, and manufacture of the parts using AM technology” (p.1775). With the limitations of only a few brands and a few styles of
pointe shoes, many professional ballerinas work with a maker to customize the fit, but this is an expensive process, and one slight difference in a pair of pointe shoes affects a dancer’s comfort significantly. When evaluating CAD models and designs, Finite Element Analysis (FEA) is a typical simulation technique that computes parameters such as stress and load distribution for a model (Azariadis, 2012). There are vast opportunities provided by AM methods, especially customization, that would alleviate problems associated with inconsistent fit in current pointe shoe models and improve the overall functionality of pointe shoes.

### 2.6 Mechanical Design Methods

In order to understand the subsequent research around the design and prototyping process, it is important to situate the work in the context of existing mechanical design. Typical mechanisms in mechanical design consist of rigid parts, which are constrained by the joints (Kobayashi, Nishiwaki, Izui, & Yoshimura, 2009); whereas, compliant mechanisms enable the mobility of flexible members and can transfer or transform motion, force, or energy (Howell, Magleby, & Olsen, 2013). Thus, the mobility of joints provides many advantages over rigid links connected at joints, including reduced wear, reduced part-count, and increased reliability (Howell et al., 2013). Regarding pointe shoes, *flexibility in the shoe is needed to roll through the ankle and up to the toes, yet strength is necessary to support a dancer’s arch*. Therefore, the nature of compliant mechanisms and moveable joints motivated the design process to verify its use in pointe shoes.

Similarly, arches are common elements used in mechanical design that allow for two distinct stable configurations (Palathingal & Ananthasuresh, 2019). Figure 12 shows the example of boundary conditions characterizing the 3D-printed arches’ bistability. Lastly, topology
optimization methods optimize a design for a given set of boundary conditions and loads. Topology optimization is beneficial to evaluate designs and determine where material may be removed to reduce overall part weight (Palathingal & Ananthasuresh, 2019). Since an important aesthetic of ballet is the lightness of movement, reducing the pointe shoe’s weight would also help with noise reduction.

![Figure 12. 3D-printed bistable arch (Palathingal & Ananthasuresh, 2017)](image)

Compliant mechanisms, bistable arches, and topology optimization are helpful mechanical design techniques that aim to deliver unique design properties and improve a model’s overall effectiveness.

### 2.7 Research Questions

This work aimed to identify the problems that ballerina’s face when wearing pointe shoes and address how AM may be utilized to explore solutions and design improvements through the prototyping process. Pointe shoes consist of many different parts such as the box, vamp, shank, elastic, ribbons that enable a dancer to rise onto their toes and perform intricate movement. As part of the design thinking process of empathizing, defining, ideating, prototyping, and testing, the work intended to answer the following research queries:
Research Query 1: What are some of the major challenges that ballerinas face?

Prior literature regarding human-centered design and empathizing with the end-user motivated this research question. To even begin thinking about additive manufacturing, it was essential to understand professional dancers’ perspectives to confirm gaps in current pointe shoes or identify new areas to investigate. Likewise, the extensive literature about biomechanics also motivated this question to capture common injuries that the participants experienced.

Research Query 2: How do ballerinas customize their pointe shoes to meet their needs?

It was necessary to answer this research question to evaluate which areas in pointe shoes dancers typically alter. In doing so, a particular component of the pointe shoe would be further analyzed. Additionally, this query allowed for any commonalities between respondents in their customization techniques to be determined.

Research Query 3: Are there any relationships between the brand of pointe shoes and the shoe area that degrades the quickest, part of the shoe with the most discomfort, type of injury, or hours of dance per week?

Since existing literature explores the impact of worn vs. new pointe shoes and their effect on ankle flexion, research question three was asked to determine the participants’ experiences. Similarly, the literature referenced the shank as being a critical area that fails first, so the research question was asked to validate those findings. In particular, this query helped to evaluate whether or not two variables were statistically significant or not statistically significant.
Research Query 4: *How can advanced design and manufacturing methods be used to enhance pointe shoe design?*

Based on existing literature surrounding compliant mechanisms, Finite Element Analysis, and bi-stable arches used in various industries with parts of complex geometry, RQ4 was asked to validate implementing these methods into ballet pointe shoes. With the large forces experienced by dancers on pointe, mechanical designs and simulation were two areas of interest, specifically for application in pointe shoes.
Chapter 3
Understanding User Needs

A study was conducted with 53 ballet dancers in various professional dance companies throughout the United States to answer key questions. Data was gained over two months from October-November. This study helped to gain insight into the perspective of ballerinas and their experiences wearing pointe shoes. The research questions investigated were: “What are some of the major challenges that ballerinas face?” (RQ1), “How do ballerinas customize their pointe shoes to meet their needs?” (RQ2) and, “Are there any relationships between the brand of pointe shoes and area of the shoe that degrades the quickest, part of the shoe with most discomfort, injury, or hours of dance per week? (RQ3).”

3.1 Design of Study

This study was designed to set the foundation for future prototyping of a pointe shoe. By focusing on fundamental research questions and better understanding professional dancers’ needs, the objective of redesigning the pointe shoe may be achieved. The survey questions were formulated based on the literature review and personal connections with dancers. After preparing the questions, a web-based survey tool called Qualtrics was used to collect and analyze responses. Table 1 shows the breakdown of the survey questions to the overarching research questions. The entire survey questions with accompanying figures may be viewed in Appendix A.

Participants were contacted via email or on the social media platform, Instagram, with information about the research project and a link to the survey to collect data on their overall experience with pointe shoes (Appendix B). Furthermore, participants were only contacted once.
but frequently passed the survey to other dance members. Another avenue for sharing the survey was contacting representatives at ballet companies and inquiring about sharing the survey with their dancers. It is important to note that no personal demographics were collected to preserve anonymity. A variety of statistical analysis programs were utilized to analyze the results, including Qualtrics Stats iQ, SPSS, Tableau, and WordStat.
<table>
<thead>
<tr>
<th>Research Question</th>
<th>Survey Question</th>
<th>Response Rate</th>
<th>Data Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.) What are some of the major challenges that ballerinas face?</td>
<td>What are the most prevalent problems in a pointe shoe to you? Please select three answers.</td>
<td>100% (53/53)</td>
<td>Qualitative</td>
</tr>
<tr>
<td>2.) How do ballerinas customize their pointe shoes to meet their needs?</td>
<td>Do you adapt your pointe shoes? If so, please explain how you adapt them to fit your needs and why? Please select all of the following protection pads/materials that you currently use. Please select which feature you think could be improved to increase the overall quality of a pointe shoe.</td>
<td>73.6% (39/53) 100% (53/53) 98.1% (52/53)</td>
<td>Qualitative/Quantitative</td>
</tr>
<tr>
<td>3.) Are there any relationships between brand of pointe shoes and</td>
<td></td>
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</tr>
<tr>
<td>3a) area of the shoe that degrades the quickest?</td>
<td>What brand of pointe shoes do you currently wear?</td>
<td>100% (53/53)</td>
<td></td>
</tr>
<tr>
<td>3b) part of the shoe with most discomfort?</td>
<td>Which location represents the most common area that fails first on your pointe shoes?</td>
<td>100% (53/53)</td>
<td>Qualitative/Quantitative</td>
</tr>
<tr>
<td>3c) type of injury?</td>
<td>Please rank the top three areas that cause you the most discomfort.</td>
<td>100% (53/53)</td>
<td></td>
</tr>
<tr>
<td>3d) hours danced?</td>
<td>Have you ever had medical problems due to pointe work? If so, briefly describe your experience.</td>
<td>67.9% (36/53)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>How many hours of pointe work do you perform each week?</td>
<td>96.2% (51/53)</td>
<td></td>
</tr>
</tbody>
</table>
3.2 Participants

The total sample size obtained from the survey was N = 53. The average participant danced a total of 29 hours per week and the median number of hours danced was 30 hours per week. It is important to mention that there were different response rates per question (Table 1). This difference in response rates occurred mainly with the open-ended questions, resulting in lower response rates.

3.3 Data Analysis

The first overarching research question of interest was: What are some major challenges that ballerinas face? The following survey question was posed to participants, “What are the most prevalent problems in a pointe shoe to you.” Participants were asked to select three problems from nine choices. An ‘other’ option was also available. A treemap was chosen to visualize what issues are more frequently experienced by professional dancers. Figure 13 shows the treemap with the total count for the various selections. The mark ‘Loud’ had the highest count at 22, and the mark ‘I can only wear one brand’ and ‘Satin rips constantly’ had the lowest selection count at 6, respectively. Additionally, ‘Shank breaks quickly’ and ‘Don’t form to my feet’ were relatively high, with a total count of 18 and 16.
Figure 13. Treemap of prevalent problems

The results reveal that as part of redesigning the pointe shoe, loud, shank breaks quickly and don’t form to my feet are important design criteria to address in new models. Furthermore, Figure 13 points to the most relevant problems to dancers and identifies which parts of the shoe to redesign first.

The second research question of interest was: How do ballerinas customize their pointe shoes to meet their needs? This question aimed to evaluate the methods used and identify any commonalities or trends between participants. A total of three survey questions were presented to participants. The first survey question asked was, “Do you adapt your pointe shoes? If so, please explain how you adapt them to fit your needs and why?”. Since this question was open-ended, a content analysis was performed to determine the linkage between words used to answer the question and visualize the relationships between entities in the data. As shown in Figure 14, the
nodes represent the frequent words participants used to describe their pointe shoe preparation process. Additionally, the lines are weighted based on the association between entities, which were determined based on frequency count. For example, the nodes cut and shank have a strong association of 0.367, whereas cut and box had a much lower association of 0.125. The three nodes with the greatest values from the data set were shank, arch, and cut. This qualitative analysis of responses highlighted the modifications dancers make, particularly to the shank area.

Figure 14. Link analysis of responses

The second survey question asked of participants was, “Please select all of the following protection pads/materials that you currently use.” There were 12 different options provided and an ‘other’ option as well. This question looked further into the types of products and tools dancers use to protect their feet and improve comfort. Figure 15 is a visualization of the results, where each color represents a different protection product. Additionally, the size of each bubble refers to the sum of
the count for each product. A packed bubble chart was selected as the visualization method because it displays many variables in a compact space. Based on Figure 15, ouch pouches (a thin pad with a gel material that helps protect toes inside the toe box) had the greatest count at 26 compared to toilet paper, where only one participant selected that material. Also, toe spaces and paper towels were frequently chosen with a total count of 11 and 10, respectively.

Another interesting finding was that only six participants selected PerfectFit inserts. PerfectFit inserts are glove-like inserts made up of moldable putty that form to the front of the foot (PerfectFit, 2020). While some participants are using this product, the development of new inserts for pointe shoes does not necessarily mean that all dancers will want to switch to the product. Additionally, the small number of participants using PerfectFit inserts highlights that an insert

Figure 15. Packed bubble chart of protection materials dancers used
does not entirely fix a dancer’s problems. Regarding the design problem, one must consider pointe shoe design improvements holistically and explore the core issues in the shoe. Moreover, this question highlights that new methods of manufacture need to be applied to the entire shoe and not one component, as the former will not solve dancers’ problems entirely.

The third survey question asked to obtain additional insights for RQ2 was, “Please select which feature you think could be improved to increase the overall quality of a pointe shoe.” Participants were asked to score five features (durability, quiet-landing, reinforced satin material, long-lasting shank, and increased comfort) on a five-point scale of the following: extremely important, very important, moderately important, slightly important, or not at all important. A 5-pointe Likert scale was used to analyze the data, where extremely important = 5, very important = 4, moderately important = 3, slightly important = 2, or not at all important = 1. Finally, a Spearman’s rank-order correlation was run to assess the relationship between features to improve pointe shoes in professional dancers (Laerd Statistics, 2018). Table 2 showcases the results from running the Spearman correlation. There was a statistically significant, strong positive correlation between the feature long-lasting shank and durability, \( r_s(3) = .900, p < 0.05 \). The strong correlation was an important finding as it emphasized the experiences of dancers who significantly value long-lasting shank and durability as features to improve pointe shoes. Additionally, there was a statistically significant, strong positive correlation between increased comfort and durability, \( r_s(3) = .900, p < 0.05 \), highlighting the importance of comfort and durability in pointe shoes. One final observation was a statistically significant, strong negative relationship between long-lasting shank and reinforced satin data, \( r_s(3) = -0.975, p < 0.01 \). Realistically, this makes sense as creating a long-lasting shank does not directly influence reinforced satin material.
Table 2. Spearman’s rho correlation between features of pointe shoes

<table>
<thead>
<tr>
<th>Spearman’s rho</th>
<th>Long Lasting Shank</th>
<th>Durability</th>
<th>Quiet Landing</th>
<th>Increased Comfort</th>
<th>Reinforced Satin Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correlation Coefficient</td>
<td>1.000</td>
<td>.900$^*$</td>
<td>.700</td>
<td>.800</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>.5</td>
<td>.037</td>
<td>.188</td>
<td>.104</td>
<td>.005</td>
</tr>
<tr>
<td>N</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Correlation Coefficient</td>
<td>.900$^*$</td>
<td>1.000</td>
<td>.600</td>
<td>.900$^*$</td>
</tr>
<tr>
<td>Durability</td>
<td>.037</td>
<td>.5</td>
<td>.285</td>
<td>.037</td>
<td>.054</td>
</tr>
<tr>
<td>N</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Correlation Coefficient</td>
<td>.700</td>
<td>.600</td>
<td>1.000</td>
<td>.300</td>
</tr>
<tr>
<td>Quiet Landing</td>
<td>.188</td>
<td>.285</td>
<td>.</td>
<td>.624</td>
<td>.322</td>
</tr>
<tr>
<td>N</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Correlation Coefficient</td>
<td>.800</td>
<td>.900$^*$</td>
<td>.300</td>
<td>1.000</td>
</tr>
<tr>
<td>Increased Comfort</td>
<td>.104</td>
<td>.037</td>
<td>.624</td>
<td>.</td>
<td>.054</td>
</tr>
<tr>
<td>N</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Correlation Coefficient</td>
<td>-.975$^{**}$</td>
<td>-.872</td>
<td>-.564</td>
<td>-.872</td>
</tr>
<tr>
<td>Reinforced Satin Material</td>
<td>.005</td>
<td>.054</td>
<td>.322</td>
<td>.054</td>
<td>.</td>
</tr>
<tr>
<td>N</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

$^*$: Correlation is significant at the 0.05 level (2-tailed).
$^{**}$: Correlation is significant at the 0.01 level (2-tailed).

To summarize the key insights from the survey concerning RQ2, one important takeaway was that dancers most frequently modify the shank and arch area in their pointe shoes. This observation was similar to the outcome in the third survey question, where a significant correlation was found between long-lasting shank and durability as improvements for pointe shoes. Overall, the survey results provide evidence and support for improving the shank area in a pointe shoe.

The third overarching research question of interest was: Are there any relationships between the brand of pointe shoes and the shoe area that degrades the quickest, part of the shoe with the most discomfort, type of injury, or hours of dance per week? For the first analysis between the brand of pointe shoes and the shoe area that degrades the quickest, participants selected from five different brands (Bloch, Capezio, Freed of London, Gaynor Minden, Grishko) or selected an ‘other’ option and chose as many areas from 1-12. Please see Appendix A (pg. 58) for the diagram with the twelve locations used in the survey. Multinomial logistic regression was performed to analyze the data and determine if interactions between independent variables predicted the
dependent variable. The brand and areas were formulated into the SPSS statistical program, and then a multinomial logistics regression method was run (Laerd Statistics, 2017). As shown in Table 3, the p-values for all areas and brands were greater than the alpha value of 0.05 (i.e., p > 0.05), with some values not calculated due to redundancy. Therefore, the data shows that area and brand are not statistically significant. The areas that participants selected as areas that fail first were not limited to one brand but consistent between pointe shoe brands.

Table 3. Multinomial logistic regression significance values (area vs. brand)

<table>
<thead>
<tr>
<th>Area</th>
<th>Bloch</th>
<th>Capezio</th>
<th>Freed of London</th>
<th>Gaynor Minden</th>
<th>Grishko</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.</td>
<td>.</td>
<td>1</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>2</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.997</td>
<td>0.999</td>
<td>0.999</td>
<td>0.998</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>4</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>5</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>6</td>
<td>0.998</td>
<td>0.999</td>
<td>0.999</td>
<td>0.998</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>7</td>
<td>0.997</td>
<td>0.998</td>
<td>0.999</td>
<td>0.998</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>8</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>9</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>10</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>11</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>12</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>

For the second analysis between the brand of pointe shoe and the part of the shoe that causes the most discomfort, participants chose from five different brands (Bloch, Capezio, Freed of London, Gaynor Minden, Grishko) or selected an ‘other’ option, and selected their top three areas from A-I, where they experience the most discomfort. Figure 16 highlights the image participants viewed to identify their discomfort locations in the survey.
Figure 16. Diagram of locations where discomfort is experienced

Similar to the previous statistical analysis, a multinomial logistic regression was performed to determine if the pointe shoe brand was statistically significant across the nine discomfort areas A-I (Laerd Statistics, 2017). Based on the results in Table 4, it was observed that the p-values for all discomfort areas and brands were greater than the alpha value of 0.05 (i.e., $p > 0.05$), with some values not calculated due to redundancy. Since discomfort area selections and pointe shoe brands were not statistically significant, regardless of the pointe shoe brand, the participants had the same problems across the shoe manufacturers. Furthermore, these statistical findings provide evidence for why redesigning the pointe shoe is needed.

Table 4. Multinomial logistic regression significance values (discomfort area vs. brand)

<table>
<thead>
<tr>
<th>Parameter Estimates - Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discomfort Area</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>F</td>
</tr>
<tr>
<td>G</td>
</tr>
<tr>
<td>H</td>
</tr>
<tr>
<td>I</td>
</tr>
</tbody>
</table>
For the third analysis between pointe shoe brand and type of injury, participants chose from five different brand brands (Bloch, Capezio, Freed of London, Gaynor Minden, Grishko) or selected an ‘other’ option and provided an open-ended response to the injuries they have experienced due to pointe work. Since the data consisted of open-ended responses, the data were bucketed into the following groups: broken bone, bunions, toenail issues, stress fractures, bone issues, chronic pain, infected blisters, tendonitis, nerve issues, and an ‘other’. Table 5 showcases the Chi-Squared test results along with the frequency of responses for the bucketed injury groups. The Chi-Square test found that the p-value was 0.635, which is greater than the alpha value of 0.05 (i.e., p > 0.05). Thus, the test highlighted no statistically significant relationship between the variables, type of injury, and the pointe shoe brand. In other words, injuries are not limited to one particular brand of pointe shoes.

<table>
<thead>
<tr>
<th>Have you ever had medical problems due to pointe work? If so, briefly describe your experience. *Note these are bucketed groups.</th>
<th>Total</th>
<th>Capezio</th>
<th>Freed of London</th>
<th>Bloch</th>
<th>Gaynor Minden</th>
<th>Grishko</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broken bone</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bunions</td>
<td>5</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Toe nail issues</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stress Fractures</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bone Issues</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Chronic pain</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Infected blisters</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Tendonitis</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nerve Issues</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Bucketed Overall Stat Test of Percentages</strong></td>
<td><strong>0.635</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Chi-Squared test between the pointe shoe brand and bucketed injuries
Lastly, for the fourth analysis between pointe shoe brand and hours danced per week, participants selected from five different brands (Bloch, Capezio, Freed of London, Gaynor Minden, Grishko) or selected an ‘other’ option and provided the number of hours they dance per week. Since the data compares brand (categorical) to the number of hours (numerical variable), an Analysis of Variance (ANOVA) was run to test the difference between the two or more means. Table 6 showcases the ANOVA results along with the frequency of responses for each range. The ANOVA test found that the p-value was 0.127, which is larger than the alpha value of 0.05 (i.e., p > 0.05). Therefore, the test determined that the relationship between brand and the number of hours danced per week was not statistically significant.

<table>
<thead>
<tr>
<th>How many hours of pointe work do you perform each week?</th>
<th>What brand of pointe shoes do you currently wear?</th>
<th>Total</th>
<th>Capezio</th>
<th>Freed of London</th>
<th>Bloch</th>
<th>Gaynor Minden</th>
<th>Grishko</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Count</td>
<td></td>
<td>51</td>
<td>3</td>
<td>20</td>
<td>8</td>
<td>7</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>≤ 15 hours</td>
<td></td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>16 - 30 hours</td>
<td></td>
<td>22</td>
<td>1</td>
<td>7</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>31 - 45 hours</td>
<td></td>
<td>17</td>
<td>0</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>46 - 60 hours</td>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>≥ 61 hours</td>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Average hours</td>
<td></td>
<td>29.0</td>
<td>31.0</td>
<td>34.9</td>
<td>30.9</td>
<td>19.6</td>
<td>19.8</td>
<td>25.0</td>
</tr>
<tr>
<td>Overall Stat Test of Averages</td>
<td></td>
<td>0.127</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Overall, the purpose of this survey was to gather insights from professional dancers and better understand the user needs - a critical factor in human-centered design methodology. Upon both qualitative and quantitative analysis, significant findings were observed. One major finding was the strong positive correlation between the characteristics dancers desired in a pointe shoe,
long-lasting shank, and improved durability (Table 2). This was significant because it helped narrow the scope of the research to focus on the shank area. Likewise, the content analysis that examined how participants adapt their pointe shoes found a large frequency between the nodes shank, cut, and arch (Figure 14). Furthermore, those results further motivated the need to begin design efforts in the shank. Another finding was that the pointe shoe brand was not statistically significant compared to the shoe area that degrades the quickest, part of the shoe with the most discomfort, type of injury, or hours danced per week (i.e., \( p > 0.05 \)). These findings were interesting because it meant that in areas where the pointe shoe fails first, part of the shoe selected with the most discomfort, and type of injury were not limited to one brand of pointe shoes. In other words, the differences from one brand to the next were not statistically different enough compared to the parameters. To summarize, survey analysis consistently identified the shank area as a location to begin development and design efforts to meet dancers’ needs.
3.4 Personal Interviews

As part of the human-centered design process, focusing on the end-user is a strategic decision that drives the design & implementation phases (Harte et al., 2017). By understanding the user needs through quantitative and qualitative research, prototypes may more effectively reflect the design requirements. The survey was an excellent way to gather insights from a moderately sized sample, where N = 53 professional dancers. Additionally, two professional dancers were directly interviewed over the phone. Each conversation was about 30 minutes and consisted of various questions that went deeper into problems with pointe shoes, such as materials used to reduce pain and design criteria to improve pointe shoes. A semi-structured interview was conducted, in line with best practices in qualitative methods with questions focused on selecting a brand of pointe shoes, the pointe shoe preparation process, and important considerations to improve pointe shoes in the future. Specifically, the following questions were asked to both participants: “How did you select your current brand of pointe shoes?”, “Could you describe how you prepare/customize your pointe shoes?” and “What are the most important factors to consider to improve the pointe shoes?.” However, as is common with semi-structured interviews, interview protocol was not constrained to these questions so insights could emerge more naturally.

The first question aimed to gather insight into how a dancer selects their pointe shoe brand. One interesting insight captured from interviewee one was the process for choosing pointe shoes in her ballet company. As part of interviewee one’s contract, she can “choose [her] shoes from 20 different makers.” However, interviewee one noted that her go-to maker from Freed of London retired, so she was “experimenting with different makers and different shoes” and has experienced an “injury from trying different styles of shoes.” Interviewee two noted that she has custom Capezio pointe shoes made, and she “switched brands four years ago when she experienced a stress
fracture wearing Freed of London shoes.” One can observe just how different each dancers’ preferences are regarding what brand they wear.

The second question’s goal was to gain knowledge of the steps taken to prepare pointe shoes so that a dancer may begin dancing. As far as adjusting shoes to be more comfortable, both interviewees used PerfectFit inserts, a moldable putty insert, an alternative to ouch pouches (a thin pad with a gel material that helps protect toes inside the box). Similarly, interviewees both stated they “put glue in their pointe shoes to extend use.” Interviewee one explained that she reduces the noise of her pointe shoes before performances by “banging the shoe against a cement or brick wall.”

Lastly, the third question sought to identify the important design requirements from a dancer’s perspective. Both interviewees one and two noted that the most crucial takeaway is to reduce noise in pointe shoes and improve the shank’s durability. An important observation that interviewee two brought up was “softening the shank allows for more articulation.” However, there is a point to which the shank loses its integrity and causes the dancer to roll too far over her toes.

The takeaways from these qualitative interviews were also consistent with the findings of the survey. In particular, the shank was identified as a critical component in pointe shoes, yet it degrades with the current construction and design. This insight links to additive manufacturing as an innovative method of manufacture because of the ability to create multi-material parts with desirable properties for dancers. The desirable properties are strength to maintain a dancer’s arch and prevent the dancer from rolling too far over and flexibility to allow the ball of the foot to articulate movement. Likewise, both interviewees mentioned that improving the shank’s durability would be a vast improvement so that they do not have to go through so many pointe shoes each
week. Overall, these interviews confirmed the survey findings and paved the way for the following research stage around design and prototyping the pointe shoes using the new method of make-Additive Manufacturing.
Chapter 4
Design of Pointe Shoes via Additive Manufacturing

The survey and interview results were consistent with the information synthesized in the literature and demonstrate a convincing opportunity to improve the ballet pointe shoe, especially in the shank area. AM was determined to be an effective method for pointe shoes because complex geometries could be captured in the 3D model, and prototypes could be easily 3D printed. Moreover, AM posed many benefits in this research, such as reducing overall pointe shoe weight, creating consistent models, and the potential for multi-material prints with rigid and flexible materials. The research question previously mentioned that motivated the design phase was “How can advanced design and manufacturing methods be used to enhance pointe shoe design? (RQ4).” The shank was identified as an area of focus for the initial modeling phase, based on the survey results that noted this component as lacking durability and support in current pointe shoe models.

4.1 Validation of Compliant Mechanisms

Pointe shoes consist of many components, each with specific materials and functions. In particular, the pointe shoe shank provides arch support, enabling a dancer to rise-up on her toes. As part of the beginning process of modeling a pointe shoe, the survey results motivated the pointe shoe area explored first. The component selected was the shank, which laid the foundation for the design stage (Figure 17). Figure 17 highlights an actual pointe shoe shank along with other components in a pointe shoe.
The SolidWorks modeling program was used to create iterations of the pointe shoe shanks and integrate compliant mechanism design. An actual pointe shoe was first used to capture the dimensions to-scale in the CAD program. By employing the knowledge of literature regarding the advantages of compliant mechanisms, each iteration consisted of modeling the shank in a unique way. The information below details the three iterations of the pointe shoe shank and the analysis performed for each design.

Case Study 1

As part of the design process of implementing Additive Manufacturing methods into the pointe shoe, the process began with utilizing SolidWorks to model the component of interest- a pointe shoe shank. This component was selected based on existing literature and the survey results that referenced the shank as an area that typically fails first in pointe shoes. In Figure 18, one can observe how a design may be incorporated to mimic the same properties of a shank. Specifically, the design was based on compliant mechanisms in other industries. The design included a
compliant mechanism through the center of the shank that tends to exhibit the most stress in existing pointe shoe shank designs. The shank is especially important for professional dancers because it supports the entire foot on pointe, and when the shank fails, a dancer must use a brand-new pair of pointe shoes. The CAD model in Figure 18 was also 3D printed using a Prusa with PLA material to visualize the compliant mechanism design better. The design created in Figure 18 was intended to help support a dancer’s arch on pointe as they roll through the ankle up onto the toes. The constraints on the right end and the left end sought to improve the range of motion in the shank.

![Figure 18. Iteration 1 of 3D pointe shoe shank](image)

In addition to creating the first iteration of the 3D model for the pointe shoe shank, Finite Element Analysis (FEA) was also performed. FEA is a simulation technique that uses numerical methods to analyze a model and identify the range of stresses present under load. Figure 19 below shows the output after running FEA on iteration 1. This simulation utilized the peak vertical force experienced by a dancer on pointe of 667 N (Hansberger, Acocello, Slater, Hart, & Ambegaonkar, 2018). Apart from this, a horizontal force of 100 N was applied to the shank to simulate the reaction forces. This FEA simulation represented a dancer performing a series of bourreés (small steps).
The FEA results in Figure 19 show the distribution of Von-Mises stress or the measure of internal forces acting on an object due to applied loads. As noted on the scale, the areas in red represent locations of high stress, and the areas in the dark blue region represent low-stress locations. Case study 1 highlights relatively moderate stress of approximately 5.209e+03 psi present on the exterior of the shank’s middle and upper regions. The remaining areas appear to show low stress of 3.463e-05 psi.
Case Study 2

As part of iteration 2 of the 3D pointe shoe shank, the design was completely altered to cover a larger area and observe what occurs in terms of flexibility and resilience. As shown in Figure 20, a compliant mechanism pattern extended from one fixed end on the left to the other fixed end on the right. Since professional dancers need flexibility and strength in their pointe shoes, this design was tested to determine if it would satisfy those requirements. Figure 20 was printed on a Prusa 3D printer with PLA as the material. While PLA would not be the best for actual implementation in a pointe shoe, it was the best material to use as part of the design and prototyping process. The particular design in Figure 20 was quite different from iteration 1. This model’s intended purpose was to observe if the compliant mechanism design extended across the entire shank would better match a dancer’s motion rolling up through their ankle up to pointe. While this design had much greater flexibility, in which the linked shape could bend upwards and backward upon constraining the two ends, it appeared to be too flexible and would not be overall beneficial in a pointe shoe.

Figure 20. Iteration 2 of 3D pointe shoe shank
As depicted in Figure 21, FEA was performed on iteration 2. The assumptions built into the model are the following: the peak vertical force experienced by a dancer on pointe was 667 N (Hansberger et al., 2018), and a horizontal force of 100 N was applied to the shank to represent a performing a series of bourrées (small steps). Case study 2 showcases significant amounts of stress located along the midsection and top, with areas experiencing stresses around 9.704e+03 psi. A quick comparison of case study 1 to case study 2 displays that the stresses are more prominent in case study 2, where areas previously in the lowest stress region switched from the dark blue range to the light blue and green stress range. The FEA analysis results are not completely surprising, as most of the material was removed through the midsection of the pointe shoe shank.

Figure 21. FEA analysis of case study 2
Case Study 3

The third iteration of the pointe shoe shank consisted of bi-stable arches fixed at the left and right ends. Figure 22 displays the five arches extending throughout the midsection of the shank. Upon 3D printing this model with PLA material and bending the ends of the shank slightly upwards, the bi-stable arches were able to transfer motion. This third iteration utilized a combination of features from iterations 1 and 2. These are noticeably characterized by the limited reduction of material throughout the shank as compared to iteration 2. As shown in Figure 22, five bistable arches were created along the shank. Since the shank is about 5 mm in thickness, the bi-stable arches had to be smaller to not go beyond the outer thickness. The design’s intended motion was to have greater support across the entire shank while allowing for the flexibility and range of motion from demi-pointe (the position where a dancer is on the falls of the feet) to pointe.

![Figure 22. Iteration 3 of 3D pointe shoe shank](image)

The following forces were used to build the model: the peak vertical force experienced by a dancer on pointe of 667 N (Hansberger et al., 2018) and a horizontal force of 100 N applied to the shank to simulate reaction forces when a dancer performs a series of bourrées. As displayed in Figure 23 below, there are clear zones towards the top of the shank and the right side where stress is approximately 1.388e+04 psi (blue-green region). The majority of the stress observed
throughout the model had the lowest stress, as noted in the scale. Based on the results in iteration 3, one can observe that the pointe shoe shank’s overall stress was lower than iteration 2, which presented many areas with stress concentrations. Similarly, iteration 1 had minimal stress; however, its design was not practical for professional dancers’ needs. Therefore, iteration 3 had the overall best combination of compliant mechanisms and arches that mimic professional dancers’ motions.

Figure 23. FEA analysis of case study 3
This research on validating the use of compliant mechanisms and bi-stable arches in a ballet pointe shoe shank demonstrated significant support for implementation in an actual model. While the 3D printing material used for prototyping the three case studies was PLA, multi-3D printed materials such as Carbon Fiber and Ninjaflex would be recommended in practice. Since existing pointe shoe shanks are made of cardboard, there is an opportunity to transform pointe shoes with advanced AM methods drastically.

The research presented in the above section focused on one component of the pointe shoe—the shank. This was an area identified in the survey as a major improvement opportunity. In reflecting upon RQ4 (How can advanced design and manufacturing methods be used to enhance pointe shoe design?), the work presented highlights that compliant mechanisms and bi-stable arches can be designed into shanks to provide the important characteristics of flexibility and strength as a dancer rolls up to pointe. Furthermore, FEA was beneficial to evaluate the stresses exhibited in the prototypes and ultimately select case study 3 to have the best overall functionality. In terms of enhancing pointe shoe designs, the opportunity of tailoring components specific to dancer foot morphology may become a reality with the adoption of AM methods. In these scenarios, one pointe shoe size was used to generate the various prototypes, but sizing could be scaled to accommodate every dancers’ preferences in the future. In the following section, thinking about the prototyping process holistically and modeling a complete pointe shoe using AM methods is considered.
4.2 Prototyping Process of a Full Pointe Shoe

This section’s work expanded upon the initial validation of compliant mechanisms as a possible application in pointe shoes. The next stage of research shifted towards understanding how to model a complete pointe shoe. Since pointe shoes have a distinct shape, capturing those features was critical in the 3D modeling process.

In rethinking the pointe shoe, a topological simulation was performed to identify areas for design improvements and to uncover any new insights not found in prior work. The main benefit of using topological optimization software was understanding how to achieve an efficient model. The simple design in Figures 24-25 included only the shank and toe box, as these are significant contributors in areas where pointe shoes degrade the fastest. A horizontal force of 100 N was applied, and a 667 N vertical force (Hansberger et al., 2018) was used to simulate reaction forces when a dancer performs a series of bourrées.

Figure 24. Topology optimization of a basic shank and box model (front view)
In Figures 24 & 25, the areas in yellow represented areas where material must be kept, whereas areas in the dark blue to the purple range defined areas where material may be removed. Figure 24 showed that most material in the box should be kept with some moderate regions located in the shank. In the side view of the model in Figure 25, one can observe the recommendation to remove material along the box’s outer edges. It is necessary to highlight that in this simplified topology optimization analysis, the method was not able to account for design aesthetics, which play an essential role in the traditional pointe shoe model.

![Figure 25. Topology optimization of a basic shank and box model (side view)](image)

While the simplified topology optimization was helpful to highlight potential areas in the shank and the box that could be reduced, it did have limitations with regards to considering the aesthetics of a ballet pointe shoe. The next avenue pursued as part of the research to better
understand AM methods applied to ballet pointe shoes was 3D scanning, intending to print a complete model.

In particular, a 3D scanning app was used to capture the geometry of a full-scale pointe shoe. Furthermore, the 3D scanning app employs a technique known as ‘photogrammetry,’ where different positions and angles from a camera use the illuminated light to generate many points that make up the entire model (3D Scanner, 2020). In Figure 26, a visualization of the generated pointe shoe scan is showcased in image two. Since the 3D scan file is a collection of points, refinement of the model through mesh analysis was needed. The mesh analysis was vital as it ensured that the model was watertight (an enclosed volume, with no holes) and that the pointe shoe had a thickness that would be printable. In Figure 26, the mesh is identified by the image called ‘create mesh.’ After the mesh analysis was performed and the model was watertight, the next step was to get the model prepared for 3D printing. After finalizing the mesh analysis, the model was converted to an STL file. Then the STL file was imported into a slicer software, and printing parameters were adjusted. The model was printed using PLA material, and supports were activated to ensure that no failures occurred. The printed 3D pointe shoe model is shown in Figure 26 as the last image. The pointe shoe’s contours, especially the toe box, and heel remained consistent with the physical shoe. This work validated the 3D scanning process for a ballet pointe shoe. While the PLA material used to print the model is not ideal given the rigid nature of PLA material, it still demonstrated the potential of applying AM methods to pointe shoes. One of the major benefits of AM in pointe shoe design is the streamlined approach to manufacturing.

Furthermore, consistency between the scanned model to the finished print was notable and emphasizes the value of using AM to create pointe shoes. Likewise, reducing the number of components in an AM model compared to traditional pointe shoes is important because, if scaled,
production time would greatly reduce with AM methods. As mentioned, the final model was printed using PLA material and the total printing time was 7 hours and 33 minutes. The shoe was printed upright with very little support material needed. While this model had to be scaled slightly smaller due to the height limitations of the 3D-printer, a to-scale model would take approximately 15 hours - 24 hours to print, depending on the selected print parameters. Based on a recent interview with shoe-makers from the Freed pointe shoe factory, one shoe-maker stated he makes “40 pairs a day or 80 pointe shoes” (Royal Opera House, 2012). Some of the significant opportunities with using AM in pointe shoes are scalability and creating many batches of shoes using industrial 3D printers. There are many future directions to take this preliminary research; however, AM does show support in applying to the ballet pointe shoe industry based on these design and prototyping findings.

![Figure 26. Design process for an entire pointe shoe](image-url)
Chapter 5

Conclusion

The purpose of this research was to identify Additive Manufacturing methods that could be applied to improve current ballet pointe shoes. Understanding the user needs was an essential aspect that motivated future work regarding design and prototyping. After uncovering the survey findings, such as the shank as a significant area for improvement, the prototyping stage began.

Three case studies of pointe shoe shanks were created by utilizing a variety of AM tools and methods. Since the shank is a critical component that enables a dancer to roll through their ankle up onto the box, a shank’s properties needed to be flexible yet strong to support the arch. Thus, compliant mechanisms and bi-stable arches were designed into the shank to validate its use. The third iteration was selected as the most optimal design based on the FEA simulation and reduced stresses. Its characteristics were more closely aligned with an existing pointe shoe. Following the shank prototypes, topology optimization was run on a simplified shank and box model to identify areas to reduce part weight and improve efficiency. The results found that most material in the box should be kept, whereas there were opportunities to reduce material in the upper portion of the shank. However, the simulation model could not consider aesthetics, which is significant in the ballet industry. Therefore, the next phase of research analyzed the feasibility of 3D scanning pointe shoes. This process involved a variety of steps, including scanning, meshing, preparation, and printing. Since the 3D scanned model was not watertight and did not have a printable thickness, mesh optimization software was used to refine the model and create solid contours. Following the optimization, the pointe shoe model was ready to be prepared for printing.
The model was printed using PLA material and included supports to ensure no errors when printing. This design process of 3D scanning to printing the model verified the feasibility of applying AM to pointe shoes.

Given these points, AM methodologies coupled with mechanical design methods of compliant mechanisms and bi-stable arches indicate a significant potential for use in pointe shoes. With the quick rate at which current pointe shoes degrade, there are opportunities to leverage AM to develop improved designs to increase durability and life.
Chapter 6

Limitations and Future Work

There were limitations to the research presented, especially with the survey. The survey was limited by the nature of data collection among professional dancers, resulting in a sample size of \( N = 53 \). While the sample size was significant because it was greater than 30, a sample size closer to \( N = 100 \) might have been more representative of the population and may have resulted in different statistical conclusions. Additionally, for some of the questions, the response rate was not 100% (53/53). This was especially apparent for the open-ended questions regarding how participants adapted their pointe shoes and any medical problems they had experienced due to pointe work. It may have been the case that participants did not have time to fill out the survey thoroughly or that the open-ended questions did not apply to them (i.e., the participant did not adapt their pointe shoes or did not experience any medical problems from pointe). Future work should address these experimental limitations and capture a larger sample size.

Limitations were also observed in the AM research surrounding the prototypes and design of the pointe shoe. Firstly, the shank was 3D printed using PLA material due to the accessibility of this material. This is a limitation because PLA provided a limited range of motion in the models. Different materials may have resulted in different conclusions about the three case study designs. Similarly, a multi-material extruder would have likely helped increase strength in critical areas of the shank like the arch. In contrast, the ends would be more flexible to allow for articulation of the toes and ankle. Indeed, future work should direct efforts to reduce these AM limitations.

Future work regarding pointe shoes should also make use of other methods within AM. With most research efforts involving biomechanics and injuries, research needs to focus on developing a better pointe shoe with the latest technological innovations. However, professionals
must be involved throughout every step of the human-centered design process beyond a survey in future work. This is important due to the nature of the ballet world, where the introduction of a new shoe can lead to controversy, as observed by the Gaynor Minden shoes, where the footwear is considered ‘cheater shoes’ by some (Hoogsteyns, 2013). A rigorous testing procedure should also be implemented in future work to test prototypes and obtain feedback from professional dancers. In doing so, refined models’ lifetime and durability might be quantified to observe just how much the changes may or may not improve the pointe shoe. Additional work using AM should directly experiment with different materials to determine the best combination for feasibility in a pointe shoe beyond the standard PLA material.

This paper motivates future work to determine the advanced design and manufacturing methods to enhance pointe shoes. Prospective studies have the potential to meet the needs of dancers when it comes to an improved lifetime of pointe shoes without significantly affecting the perceptions of the ballet world. This preliminary work in a field with little research being applied to pointe shoes showcases the major opportunity that may be fulfilled with an improved model. By bringing engineering methods into pointe shoes' manufacturing process, efficiency and product consistent would likely improve. Pointe shoes will continue to shape the art of ballet, but there are opportunities to advance its design and material construction.
Appendix A

Survey of Professional Dancers

Q1  Do you adapt your pointe shoes? If so, please explain how you adapt them to fit your needs and why?

Q2  What brand of pointe shoes do you currently wear?

- Capezio
- Freed of London
- Bloch
- Gaynor Minden
- Russian Pointe
- Grishko
- Prima Soft
- Sansha
- Gamba
- Chacott
- Other (please specify)
Q3 Please rank the top three areas that cause you the most discomfort.

Rank the top three areas from the image above.

☐ A
☐ B
☐ C
☐ D
☐ E
☐ F
☐ G
☐ H
☐ I
Q4  What are the most prevalent problems in a pointe shoe to you? Please select 3 answers.

- [] Loud
- [] Shank breaks quickly
- [] Expensive
- [] Satin rips constantly
- [] I can’t feel the floor
- [] Don’t form to my feet
- [] Toe box is painful
- [] Overall causes discomfort
- [] I can only wear one brand
- [] Other

Q5  Have you ever had medical problems due to pointe work? If so, briefly describe your experience.

Q6  How many hours of pointe work do you perform each week?

0  10  20  30  40  50  60  70  80  90  100

Click to write Choice 1
Q7 Which location represents the most common area that fails first on your pointe shoes?

Please select all that apply from the image above.
Q8
Please select which feature you think could be improved to increase the overall quality of a pointe shoe.

<table>
<thead>
<tr>
<th></th>
<th>Durability</th>
<th>Quiet landing</th>
<th>Reinforced satin material</th>
<th>Long lasting shank</th>
<th>Increased comfort</th>
</tr>
</thead>
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<td>Extremely important</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
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<tr>
<td>Very important</td>
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<td>☐</td>
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<tr>
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<tr>
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<td>☐</td>
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<td>☐</td>
</tr>
<tr>
<td>Not at all important</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

Q9
Please select all of the following protection pads/materials that you currently use.

- [ ] Gel toe sleeves
- [ ] Gel or silicone inserts
- [ ] Ouch pouches
- [ ] Lambs wool
- [ ] Paper towels
- [ ] Band-Aids
- [ ] Toilet paper
- [ ] Athletic tape
- [ ] Toe spacers
- [ ] PerfectFit inserts
- [ ] Other (please specify)
Appendix B

Email Distributed to Participants

Dear (Name),

My name is Keri Nicolich and I am a student at Pennsylvania State University. I am working on a research project investigating pointe shoes and how to improve the structural integrity to fit the needs of professional dancers. In order to create an innovative model, I am seeking the help from professional dancers. If there is any way that you could send the following survey link to the dance company that would be greatly appreciated. I sincerely thank you in advance for your help.

Survey link: https://qtrial2018q3az1.az1.qualtrics.com/jfe/form/SV_1KRvlcwb02jQi7

Respectfully,
Keri

Keri Nicolich
The Pennsylvania State University, 2021
College of Engineering
E: kerinicolich@gmail.com
BIBLIOGRAPHY


ACADEMIC VITA

Keri A. Nicolin

EDUCATION
The Pennsylvania State University
Bachelor of Science in Industrial Engineering
Minor in Entrepreneurship and Innovation
Schreyer Honors Scholar
- Honors: Dean’s List, President’s Freshman Award, Industrial and Manufacturing Engineering Scholarship
- Business Skills: Adobe Illustrator, Microsoft Suite (Excel, PowerPoint, Word, Project, Publisher)
- Programming Skills: SolidWorks, MATLAB, VBA, Minitab, Arduino, Power BI, R

WORK EXPERIENCE
Nike, Inc.
Footwear Product Category Engineering Intern
Beaverton, Oregon (Virtual)
- Present product design recommendations to increase tennis serve verticality by analyzing footwear finite element analysis (FEA) simulations
- Standardized the shoe last development process by creating a process flow which established a consistent, repeatable, and scalable fit across all footwear models
- Developed a strategy that improves inclusion and diversity on Nike’s digital platforms by surveying 225 consumers
- Engaged in over 20 technical training sessions with Nike experts in pattern making, chemistry, tooling, and sustainability

ExxonMobil Global Projects
Cost Engineering Co-op
Beaumont, Texas
- Improved engineering contractor report quality by embedding VBA validation to proactively flag data input errors; conducted four training sessions with ExxonMobil contractors to drive alignment on the revised report
- Collaborated with process design and project engineers to produce a cost estimate for wireless technology implementation
- Centralized onboarding resources in SharePoint to increase new hire productivity for Beaumont Area Projects (BMAP)

GE Aviation
Environmental, Health & Safety Intern
Greenville, South Carolina
- Facilitated a 25-minute GE required training to educate over 325 employees on Hazard Communication (HAZCOM) and Personal Protective Equipment (PPE) safety requirements
- Led three roundtables with 40+ machinists and support team members to evaluate site safety and culture; communicated findings to human resources (HR) which has resulted in a subsequent culture fundamentals training for business leaders
- Created an all-encompassing safety and site security information guide for 50+ contractors to increase user adoption
- Implemented 5S lean methodology to organize cleaning equipment for 14 manufacturing lines

GE Aviation
Coatings & Special Processes Sourcing Intern
Evendale, Ohio
- Forecasted part workload from a previous Long-Term Agreement (LTA) to minimize quantity over/understatement
- Documented Request for Quotation (RFQ) changes to ensure accuracy of pricing and capacity details for vendor bids
- Managed the onboarding content for sourcing employees to expedite system access
- Coordinated with the engineering team to record customer problems and implement changes that remediate system errors

ENGINEERING RELATED EXPERIENCE
Research Experience for Undergraduates (REU)
Application of Compliant Mechanism Designs in Pointe Shoes
State College, Pennsylvania
- Generated prototypes using additive manufacturing and topology optimization software to minimize material cost
- Applied FEA internal stress testing results to create an optimal pointe shoe design
- Validated the use of compliant mechanisms to enhance pointe shoe strength and flexion

Hedy’s Garage Entrepreneurship Startup Program
State College, Pennsylvania
- Crafted a pitch competition script that won third-place out of 40 initial applicants and received a $5,000 award
- Explored live-streaming customer market segments by creating 30+ connections across sport and entertainment industries

ACTIVITIES
- THRED (Technology and Human Research in Engineering Design) Lab Researcher, Orchesis Dance Company, Maker Club