Polyurethane Inserts for Comfort and Injury Prevention while Dancing En Pointe

by

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Table of Contents

Abstract

Pointe shoes have been made using the same rudimentary materials and methods for the past 200 years, and for this reason modern dancers lack access to more sophisticated equipment. Presented here is an insert that will last longer than a typical shoe, improve fit around the toes, and increase comfort. The insert was made from Simpact© 60A, a commercially available two-part polyurethane. Samples were tested cyclically at rates of 2, 4, and 6 mm/s in order to ensure that they would not wear out and become unusable. Inserts were also molded to the foot of a semi-professional dancer and tested to measure the force on the hallux. Using a polyurethane insert, this force was reduced to less than 10% of a ballerina's body weight. This is a dramatic improvement from an unmodified shoe, where over 60% of the dancer's weight can be on the hallux, and even a shoe with an epoxy modification, where the pressures are around 20% of the body weight. These inserts also lie completely inside the toe box of the pointe shoe, meaning they have no effect on the aesthetics of ballet. They increase comfort through improved fit and decreased force, allow ballerinas to maintain feel of the floor, and are predicted to extend the life of the pointe shoe.

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List of Figures and Tables

Figures

Tables

Introduction and Motivation

1.1 The Origins of Ballet

The centuries-old history of ballet began with the marriage of Catherine de Medici to the French king Henry II. Henry's court reveled in extravagant banquets and tournaments, but they were little in comparison to the entertainment of the Italians. These included graceful dances known as *balli* and *baletti*, which consisted of simple yet rhythmic steps. Catherine's marriage brought with it her Florentine tastes, and eventually the French court embraced what they called *ballet*.[1]

The 1581 work, *Ballet comique de la Reine*, is commonly accepted as the first ballet, and was the first to demonstrate any sort of formal discipline.[2] It became hugely popular, allowing ballet to flourish and become a central part of the French court. But it was not until the reign of Louis XIII, a devoted dancer, that the art began to resemble its current form. Ballet began to incorporate acrobatic elements, while doing away with the stuffiness of medieval dance.[1] This new take on ballet caused an enormous surge in popularity, and the courts at which it was performed became crammed with spectators, all hoping to catch a glimpse of the king.[1]

Ballet may have flourished under Louis XIII, but it was during the reign of his son Louis XIV, the so-called Sun King, that it became a true art. Previously, ballet had been a peacetime exercise, akin to fencing or equestrianism.[1] Louis XIV's establishment of a new dance academy elevated the status of ballet masters, and his patronage of the academy rebranded ballet as a noble art- *la belle danse*.[1] Danced predominantly by men, ballet became central to court etiquette. A young man who did not know how to dance or who did clumsily could be humiliated and ostracized by the court, so hundreds of dance schools opened to educate young gentlemen in grace, manners, and poise.[1]

It was also during this time that ballet was first put on paper, allowing its popularity to spread throughout Europe. Ballet masters transcribed steps and formations into volumes. These volumes were not meant to record entire choreographies. Rather, the idea was to break ballet down into the many different elements that could be combined into a production.[1] At its very center: the five noble positions, from which every step derived. The result was the standardization and expansion of the art, explaining the prevalence of French in modern ballet terminology.[1]

Over time, ballet moved onstage, evolving from a social dance to a theatrical one. The Paris Opera, then known as the Royal Academy of Music, was founded in 1669.[1] Earlier works performed there were very similar to the dances of the royal courts, but the emergence of *comédie-ballet* and *tragédie-ballet*, added a new element of dramatic consistency to ballet. These new styles made ballet more entertaining, and it developed into a dance style that emphasized lightness through graceful leaps and rapid footwork, losing the pomp that the court had placed upon it. Social dance had become simpler, but ballet became more complex.[1] This divide, as well as the establishment of a professional dance school in 1713, led to the rise of ballet as a theatrical art.

1.2 A Short History of Ballet Shoes

17th-century France had an interesting obsession with feet.[1] *La belle danse* may have involved elaborate costumes and backdrops, but the art truly revolved around the feet. When ballet was initially transcribed, most bodily movement was left undetermined. In contrast, every motion required of the foot was determined in a very exact manner.[1]

Those movements were so specific, it may be the reason that each ballet movement is called a step.

The original ballet dancers performed in street shoes. Men would dance in square-toed shoes with a wide heel in the back, while women wore more pointed shoes with a taller and narrower heel located not in the back of the shoe, but the instep.[1] These shoes did not differentiate between left and right foot, and the heel prevented dancers from performing many technical movements.[1,3] Eventually, the heel disappeared, and dancers began to wear the slippers that are common even to this day.[3]

Many ballet performances involved the use of wires and pulleys in order to create an illusion of floating.[1,3] But as ballet became a more technical art, there grew a desire to dance without the assistance of these wires.[3] In 1832, Marie Taglioni became the first ballerina to dance an entire performance unsupported and on the tips of her toes, rising en pointe to perform pirouettes, arabesques, and relevés for awestruck audiences.[4,5] Taglioni's pointe shoes squeezed her toes into a narrow tube of satin, providing a thin point on which to dance. Since then, pointe shoes have evolved to include a flatter and more robust platform, which better accommodate the demands on a dancer's foot.[5]

1.3 The Current State of Pointe Shoes

Even though ballet is viewed primarily as an art, ballerinas must develop the agility, endurance, and strength that are required of any professional athlete. And as in any sport, dancing requires a specialized set of equipment. A ballerina's most important tool is her pair of pointe shoes, which are composed primarily of a toe box, shank, and outer material. The toe box, which helps to protect the toes and provide support to the dancer, is made from layers of paper and canvas that are saturated with glue, materials which are extraordinarily similar to those used in the earliest pointe shoes.[4,6]

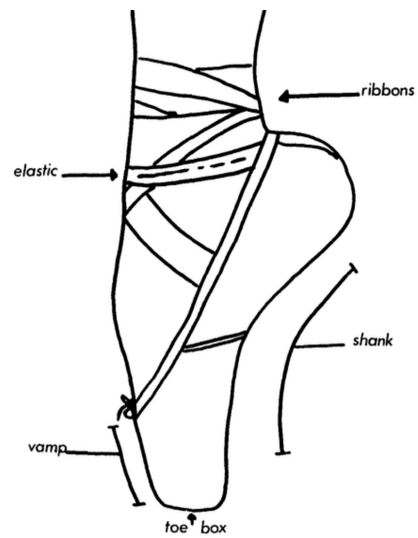

Figure 1: A diagram of the pointe shoe. Important characteristics, such as the toe box and shank, are labeled.[7]

There are currently a number of designs that focus on more ergonomically shaped pointe shoes, but there has not been much research on materials replacement or improvement.[8] Recently, pointe shoe companies such as Gaynor Minden have begun to implement more modern materials into the shoe, using an elastomer in the toe box that lasts longer and requires no breaking in.[5] Unfortunately, these shoes are not used as widely as one would expect, as they must be fitted perfectly, and are considered by some dancers to facilitate dancing en pointe, giving them the reputation of "cheater shoes".[9]

One of the biggest considerations when purchasing a pair of pointe shoes is the proper fit, as ill-fitting shoes can put dancers at heightened risk of injury.[5,6] Professional ballerinas can get custom-made shoes by sending in their specifications to pointe shoe manufacturers such as Freed of London, but those just starting out or even dancing at the pre-professional level have to contend with the ready-made options. [10] Most dancers break in their shoes before use, which provides an alternative way to get a customized fit.[5] And while breaking in shoes does somewhat improve the fit around the foot, this process also degrades the mechanical properties of the toe box,[8] shortening its life. An average pointe shoe is expected to last around 12 hours of dance,[11] but professional ballerinas might declare a pair to be unusable after just one day of dance, or even halfway through a performance.[6,10] At around $80 per pair of shoes, dancing en pointe can incur enormous costs for both individuals and ballet companies. For example, the New York City Ballet budgets half a million dollars per year for pointe shoes alone.[10,11]

Dancing en pointe places an enormous amount of pressure on the forefront of the foot.[12] The injuries and deformities that arise from this pressure are commonly accepted as a part of ballet, a necessary evil for those who aspire to a career in dance.[13] One of the reasons for this is that padding, which could improve comfort and relieve some of the load on the toes, interferes with the ballerina's feel of the floor.[8] Many ballerinas are unwilling to sacrifice this aspect of en pointe dancing, as it allows them to know exactly how their shoe is making contact with the stage, and losing feel of the floor could adversely affect their balance and technique.[8]

1.4 Research Objectives

Compared to other professional sports, there is a clear lack of materials-focused research on ballet equipment.[8] This is likely due to the fact that ballet is an art with enormous respect for tradition and a tendency to resist change.[9] It is only in recent years that dancers have begun to think of themselves as athletes in addition to artists, and as such companies like Gaynor Minden have met some degree of success. This shift in thinking implies that there are many opportunities to use modern technology and sophisticated materials to improve the properties of pointe shoes in a way that could be accepted by the ballet community at large.

An informal survey conducted in fall 2015 revealed that ballerinas value comfort above all other qualities in their pointe shoes, and comfort of the toe box was shown to be most important.[8] Comfort while dancing derives from a proper fit around the foot, or cushioning of the toes. Orthotics have not been explored as an option, due to the tight fit of the shoes, and padding is generally rejected due to interference with the feel of the floor.[5,8] The informal survey also revealed the importance of the traditional aesthetics in ballet. Changes such as orthotics or a completely new shoe design would be likely to change the shape of the arch, altering the aesthetics of dancing en pointe and thus creating an unwelcome change.[8]

This research focuses on developing a new type of insert for pointe shoes. The inserts will be placed inside the shoe prior to dancing and will mold to the shape of the dancer's foot, thus creating a better fit than can be achieved by the traditional break-in process. This will also extend the life of the pointe shoes, as the mechanical properties of the toe box will not be degraded during breaking-in. Furthermore, the inserts will not interfere with the feel of the floor, as their main purpose is to redistribute the force on the foot- shock absorption will be limited, and the materials used are stiff enough to avoid any feeling of dampening. By using advanced materials to improve fit, comfort, and life of a pointe shoe, this research will serve to modernize ballet equipment and enhance the skills of ballet dancers.

Biomechanics of Ballet

2.1 Weight Distribution while En Pointe

When dancing en pointe, a ballerina places the entirety of her weight on the tips of her toes- the metatarsi.[4,5] This weight is distributed between pressure directly on her toes, and friction along the interior of the shoe.[12] In a traditional pointe shoe, a ballerina might put as much as 80-85% of her weight on her forefoot, with frictional forces accounting for the remainder of the weight.[12] This presents a problem because the toes are not meant to bear this much weight- larger bones located farther up the foot are much more capable of doing so.[12]

Even among the different toes of the foot, there is an uneven distribution of weight.[12] The hallux, or big toe, bears the greatest amount of weight while en pointe.[5] This is because in most dancers, the hallux is the longest toe, so it is the one with the greatest contact with the platform of the shoe.[14] Feet with toes of equal lengths will inherently produce a better distribution of weight, but the majority of non-professional dancers rely on some form of padding (lambs-wool, cotton, or more modern solutions such as silicone) in order to absorb and better distribute their weight.[14]

Figure 2: A cast of the foot while en pointe. Note that the hallux is completely in contact with the platform (bottom) of the shoe, while the second toe is only partially in contact with the platform. Other toes are not in contact.[12]

2.2 Common Injuries

Ballerinas are extremely prone to injuries. In fact, most ballerinas will say that pain and injury are a necessary part of dancing. Of these, the most common are injuries to the ankle and foot.[6]

2.2.1 Bunions

Bunions, or *hallux valgus*, are among the most common ballet injuries. Bunions can arise from a toe box that is too tight, or improper technique while dancing en pointe.[15,16] One of the most common causes of bunions occurs when a dancer performs a relevé (stands en pointe) but pronates her feet.[7] The subsequent shear places pressure on her first metatarsophalangeal joint (MTPJ), which is the joint between the metatarsal and proximal phalangeal joints on the big toe.[7] Not all ballerinas will suffer from bunions,[15] but they are so common that there exist patents for "bunion protectors", specialized bandages to reduce bunion pain, and even "bunion correctors".[17–19]

There are two types of bunions seen in ballerinas- slowly and rapidly progressive bunions. Of the two, slowly progressive bunions are more common and usually less painful.[15] Slowly progressive bunions allow dancers to maintain a normal range of motion, as the MTPJ is still congruent, or properly aligned. They can be treated through the use of padding or stretching, and surgery is not usually needed during the dancer's career.[15] Rapidly progressive bunions are much more severe, causing extreme pain to dancers. Padding can usually help relieve the initial pain, but dancers suffering from rapidly-progressive bunions will almost always require anti-inflammatory medication and eventual surgery.[15]

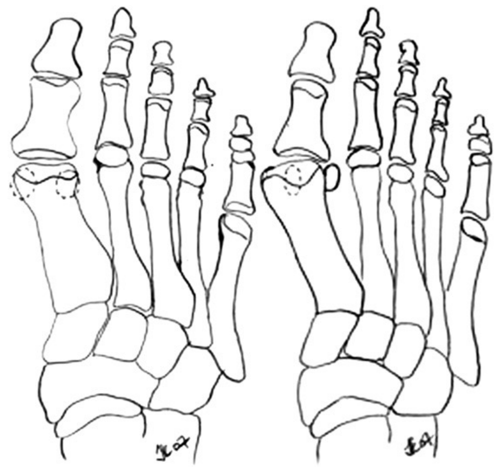

Figure 3: Bunions. Left is a diagram of the bone structure of a foot suffering from a slowly-progressive bunion, and to the right a rapidly-progressive bunion. Note the difference in angle and alignment of the first MTPJ.[15]

Visually, the difference can be subtle. In both cases, the big toe is pointed inwards towards the other toes. However, the first MTPJ is still aligned in the slowly-progressive bunion, while the rapidly-progressive bunion results in an incongruent joint.

Bunions are not just problematic in and of themselves; there are a number of secondary issues that can arise. Stress fractures and tendonitis are also common in ballerinas who suffer from bunions.[15] While these issues do not require surgery, they can cause a ballerina to miss out on a few weeks of practice and sometimes even performance, jeopardizing her career.

2.2.2 Corns and Calluses

Callosities, which are divided into corns and calluses, are not career-threatening like bunions, but are still capable of producing a good deal of discomfort in dancers. Unlike bunions, these are common to all types of dancers in all styles of dance.[20] Callosities occur in areas of the body that are exposed to high friction or pressure, in order to preserve the skin from blisters. Keratinization occurs, a process by which epidermal cells are filled with keratin, producing a thickened and toughened layer of skin.[21]

Calluses are usually broad and flat; they can occur at any part of the body, and do not usually cause pain. For this reason, treatment is not usually necessary. Corns, on the other hand, are only found on the foot, and can be extremely painful.[22,23] Corns include a central core, which is a major source of pain and inflammation on the toes.[22] One of the best ways to relieve the pain from corns is to use a corn cap or foam padding, with a hole cut out the size of the corn.[20,23] Corns can also be soaked in warm water for softening and removal with a pumice stone.[23] However, most treatment of callosities should involve both pain relief and alleviation of the cause, in order to prevent recurrence.[22]

Polyurethanes

3.1 Basic Chemistry

Polyurethanes were explored as the material of choice for this project. This is due to their very flexible chemistry, as well as the low heat produced during curing. Polyurethanes can be divided into two main types: elastic polyurethanes, which are used in flexible foams or elastomers, and rigid polyurethanes, which are used for more structural purposes.[24] The stiffness of a polyurethane depends on its cross-linking density, which is directly related to the kind of oligo-polyol used during synthesis. Longer chains and a higher molecular weight will result in more amorphous or elastic polymer with a lower cross-link density, while shorter chains with lower molecular weights result in stiffer, crystalline polymers with a much higher cross-link density.[24,25]

Polyurethane linkages are typically formed by the reaction between an isocyanate and hydroxyl group.[24] There are two types of reactions that can occur to create a polyurethane, and they result in either urethane or urea linkages. Both reactions require a terminal hydroxyl on the oligo-polyol, but a urethane linkage requires alcohol, and a urea linkage can be created using water.[24] The urethane linkage is formed in a very straightforward manner: the hydroxyl and isocyanate simply come together to synthesize a urethane. This reaction is exothermic, releasing about 100kJ/mol of heat.[24]

$$\text{R-N=C=O} + \text{HO-R'} \rightarrow \text{R-NHCOO-R'}$$

Figure 4: Reaction of isocyanate with alcohol to form a urethane linkage.

The urea-forming reaction is in fact a two-step process. In the first place, the isocyanate reacts with a molecule of water to form an carbamic acid, which is unstable and decomposes into a molecule of carbon dioxide and an amine. This amine very quickly reacts with another isocyanate in order to form a urea linkage. This reaction is more exothermic than the production of a urethane linkage, releasing roughly 200kJ/mol.[24]

$$\text{R-N=C=O} + H_2O \rightarrow [\text{R-NHCOOH}] \rightarrow \text{R-NH}_2 + CO_2$$
$$\text{R-NH}_2 + \text{O=C-N-R'} \rightarrow \text{R-NHCONH-R'}$$

Figure 5: Reaction of isocyanate with water to form a urea linkage.

3.2 Stiffness

The Young's Modulus (Y) is used to measure the ability of a given material to deform elastically. It is calculated as follows:

$$\sigma = Y\varepsilon$$

Where σ is uniaxial stress, given in Pascals, and ε is the uniaxial strain, given as a percentage. However, it is not always possible to report stress and strain as experimental values; usually they are calculated as follows:

$$\sigma = \frac{P}{A} \qquad \varepsilon = \frac{l_0 - \Delta l}{l_0}$$

Where P is the applied load in Newtons, A is the area in m^2 over which the load is applied, l_0 is the original thickness, and Δl is the change in thickness, or amount of deformation, that occurs when a load is applied. Since strain is calculated as a percentage, the units for l_0 and Δl must be the same.

In addition to the cross-link density, the mechanical properties of a polymer depend on the rate at which it is strained. If the same load is applied at a higher speed, the polymer chains will have less time to rearrange, and the sample as a whole will behave more stiffly.[26] In addition, it will have a more defined elastic region.[25] For this reason, it is important to know both the maximum load applied, as well as the strain rate. One can compare the behaviors of a particular polymer by applying loads at strain rates over several magnitudes, though these rates typically do not exceed $10^{mm}/_{s}$.[25]

3.2.1 Energy Absorbance

The toughness of a material can be calculated as the total energy absorbed before failure, and is given in units of energy per volume:

$$E_{tough} = \int_{\varepsilon_0}^{\varepsilon_f} \sigma \, d\varepsilon$$

Where ε_0 is the original strain (typically 0), and ε_f is the strain at failure. This equation can be slightly modified and used in order to calculate the total energy per unit volume absorbed by a material upon impact, also known as the shock absorbance. Since toughness is the measure of overall energy absorbed until failure, it makes sense that the energy absorbed at any given strain could be calculated by replacing ε_f with ε, the strain undergone by the material. Thus, energy absorbance can be calculated as:

$$E_{abs} = \int_{\varepsilon_0}^{\varepsilon} \sigma \, d\varepsilon$$

Additionally, the energy absorbed during loading can be interpreted graphically, by taking the area underneath the stress-strain curve.

3.2.2 Shore Hardness

Polyurethane slabs are typically sold according to shore hardness, which is a description of hardness. It is measured as the resistance against indentation by a harder material, and is considered a property of the material at a certain temperature. There are two commonly used scales- Shore A and Shore D. Shore A is typically used for softer polymers and elastomers, while Shore D is used for harder materials.[27] Most polyurethanes are sold according to a Shore A measurement; a sample with a shore hardness of 40A is considered medium-soft, while one with a shore hardness of 80A is considered hard.

3.3 Health Hazards of Polyurethanes

Cured polyurethanes are not toxic, but the same cannot be said of its uncured components. The isocyanates used in the synthesis of polyurethane are known to cause irritation to the skin, nose, or eyes.[28] In addition, isocyanates are sensitizers, meaning that repeated exposure is likely to increase risk of an allergic reaction.[29] This allergic reaction can be triggered by just a small amount of isocyanate in the air, if the individual has been exposed to enough of it in the past.[30] OSHA, the CDC, and the California Department of Public Health all recommend avoiding isocyanates if an individual who works closely with them begins to develop unexplainable symptoms such as eye-irritation, wheezing, or chest-tightness. [28–30]

The best way to prevent an allergic reaction to isocyanates is to limit contact with them. This can be done by using ventilation, to limit respiratory exposure, or through the use of personal protective equipment, such as gloves.[29] Neoprene, nitrile, or butyl rubber gloves are all recommended as superior options to latex.[30] Though its toxic nature may render polyurethane a non-ideal material for such a product, the short time frame of the project meant that any materials needed to be easily acquired or modified. Future iterations should involve less toxic materials with similar mechanical properties, such as silicones.

Experimental Procedure

The first step in developing these inserts was to choose an acceptable material. This required two main stages. The first was a qualitative assessment by a pre-professional ballerina, in order to understand which shore hardness would allow for the maximum shock absorption, without adversely affecting her feel of the floor. Afterwards, square slabs of polyurethane and silicone were tested on an Instron machine in order to characterize their mechanical properties.

After careful deliberation, the decision was made to proceed with a polyurethane model, as opposed to a "skin safe" silicone. Although polyurethanes are known to be skin irritants and can pose other health hazards, their chemistry is much more flexible. Considering the scope and time constraints of this project, it made the most sense to exploit the properties of polyurethanes and produce a preliminary prototype. However, great concern was had to ensure safety as much as possible and avoid direct contact with the polyurethanes for both dancers and scientists.

4.1 Qualitative Assessment of Samples

Six slabs of 6-inch by 6-inch dimensions and a variety of shore hardnesses were ordered from McMaster Carr. Three of these slabs were polyurethane, and had shore hardnesses of 80A, 60A, and 40A. The other three slabs were silicones, with shore hardnesses of 60A, 50A, and 40A.

The ballerina performed a number of qualitative tests in order to determine an acceptable range of shore hardness. First, she took the slabs and stressed them in her hands, bending them and attempting to stretch them. After playing with the slabs for a few minutes, she lined them up on the ground and took a step onto each slab while en pointe, comparing the feel of the rubber surface to that of the floor and making qualitative observations. In this way, she was able to test the feel of the floor, which she hoped to maintain, and the energy absorption, which would also be beneficial. The purpose of this test was to get direct feedback from a potential user, so that subsequent work could focus on polymers that would fit a dancer's needs.

4.2 Instron Characterization

After the ballerina finished reviewing the slabs, polyurethane of the appropriate shore hardness was placed in an Instron® Model A591-4 Universal Testing Machine for characterization. The purpose of this procedure was to determine the stiffness, shock absorbency, and fatigue behavior of the polyurethanes.

4.2.1 Stiffness and Energy Absorbance

In order to test the stiffness and energy absorbance, samples of 60A polyurethane were compressed up to a load of 700N. This load was determined because it is equivalent to a weight of 157 lbs, which is the slightly below the average weight of an American woman. Since most ballerinas weight less than the average woman, 700N was expected to account for more weight than a ballerina would ever need to place on her toes.

The samples were compressed at rates of 2 mm/s, 4 mm/s, and 6mm/s. They were tested at different rates in order to compare the stiffness of the polyurethane in different scenarios. Since polymer behavior is rate dependent, multiple rates were used to compare the total energy absorbed.

Following compression, the results were graphed accordingly and used in order to calculate the total energy absorbed by the samples. Their density was calculated in order to understand its relationship to the mechanical properties of the samples.

4.2.2 Fatigue Behavior

Since a ballerina takes many steps while en pointe, her shoes (and as such, any of the components of the shoe) must be able to withstand a great deal of fatigue. For this reason, it was important to study the behavior of the commercial polyurethane over many cycles of loading and unloading.

The fatigue behavior of polyurethanes was measured using the same Instron to subject samples to 1000 cycles of loading to 700N, followed by unloading. The samples were loaded at rates of 2 mm/s, 4 mm/s, and 6 mm/s. These were the fastest rates that the Instron was able to test cyclically. From graphs of previous ballerina testing, it was calculated that a hop lasts about half of a second- a very short amount of time. 6 mm/s resulted in a loading time of slightly above half a second, indicating that it would be capable of producing strain rates similar to what the inserts would need to withstand within a shoe.

The polyurethane samples were tested cyclically on their own, in order to ensure that the material itself would be able to withstand en pointe conditions.

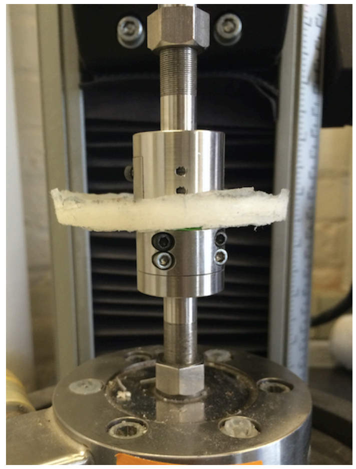

Figure 6: Experimental setup for Instron testing.

4.3 Ballerina Testing

Previous research on ballet shoe inserts confirmed the effects of improving fit when measuring the pressure on a dancer's hallux. In an unaltered pointe shoe, the hallux supports over 60% of the dancer's weight, while the original epoxy modification lowered that percentage to less than 20%.[8] This insert would have been a success, had it not been for the extreme heat generated during the cure of the epoxy. This heat produced a great deal of discomfort and even pain for the ballerina, rendering it nonideal.[8] Acknowledging that the original research demonstrated the benefits of a customized fit, this project aimed to improve the ballerina's experience even further through the shock absorption and limited heat release of a polyurethane insert.

Simpact® 60A , a commercially available 2-part polyurethane, was used to create the inserts. First, the ballerina's feet were sheathed in Saran Wrap. This was done in order to avoid direct skin contact with the polyurethane. Additionally, Saran Wrap was used to line the interior of the pointe shoe, in order to prevent the polyurethane from seeping into the fabric of the toe box. Once the foot and shoe were prepared, 2mL of each component, A and B, were mixed together and poured into the shoe. Then the ballerina inserted her foot and allowed the polyurethane to cure around it, molding to the shape of her foot.

Once the polyurethane had fully set, the inserts were tested using the same procedure as was used in testing epoxy modifications- a hop en pointe.[8] This procedure involved the ballerina standing on a force plate, with a force sensor secured to the tip of her hallux. The test required the ballerina to stand with her foot flat on the force plate, quickly push herself onto the pointe position, lower herself, and repeat. This was done three times, using the polyurethane-based insert. The results of were compared to those using a brand new shoe, as well as a shoe with the epoxy modification.

Results

5.1 Materials Selection

After bending and feeling the different slabs, as well as standing on them en pointe, the ballerina made a number of qualitative assessments. Overall, she considered the silicone to be more shock absorbent than the polyurethane, something she considered to be a good thing. However, she did not believe that the difference between the silicone and polyurethane was noticeable enough to merit one over the other. Rather, she considered that the proper stiffness was the most important quality of the insert.

Material	Hardness	Comments
Polyurethane	40A	Very soft, easy to bend, but upset her balance when she went en pointe.
	60A	Provided some absorbance, but not so much that it felt unnatural
	80A	Too hard, felt no difference between the slab and the floor

Silicone	40A	Too soft to dance on- same issues as the polyurethane slab
	50A	Felt the best in terms of hardness, and still felt comfortable dancing on top of it.
	60A	Felt slightly better than the 60A polyurethane, but the difference was not huge

Table 1: Ballerina feedback (slabs). Qualitative feedback from the ballerina regarding the silicone and polyurethane slabs.

5.2 Instron Characterization

A Mathematica program was written for the purpose of analyzing all of the data. There were two sets of code written: one to calculate the Young's Modulus and shock absorption of a sample strained at different rates, and one to analyze the change in behavior over time. Samples that were compressed cyclically did not show significant wear at the end of testing. This is to say, there were no visible signs of crumbling, and the samples seemed intact, though more compact. Graphs detailing the cyclic loading, with the linear regime indicated, can be found in the appendix.

Strain Rate (mm/s)	E_y (MPa)	E_{abs} at σ= 700N (kJ)	Density (g/cm^3)
2	2.89	12.98	0.96
4	7.04 2.59	0.91 20.87	3.95 0.91
6	3.05	17.91	0.74

Table 2: Young's Modulus (E_y) and energy absorption (E_{abs}) at different strain rates. Values calculated for a polyurethane slab of shore hardness 60A, strained to the same load but at different rates. Two trials were tested at 4mm/s

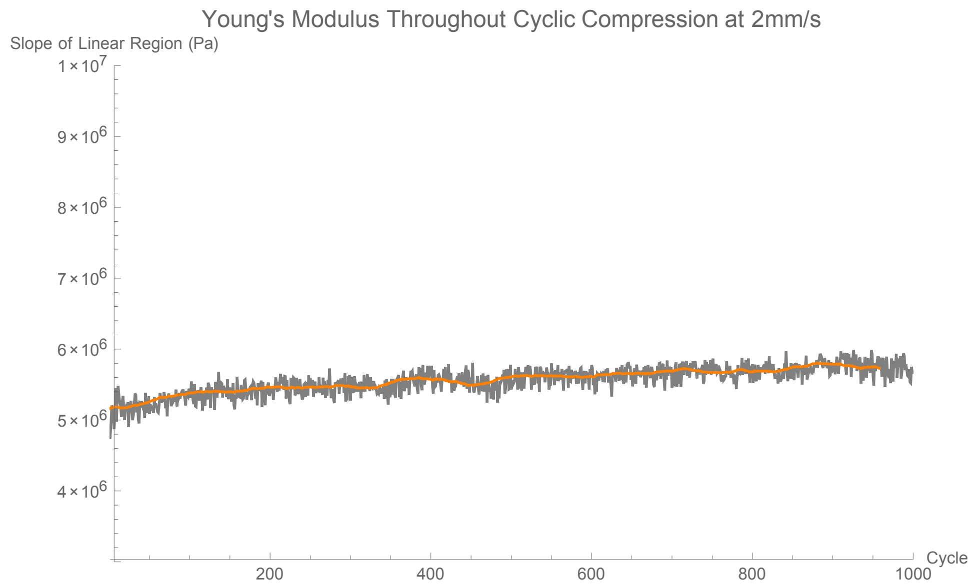

Figure 7: Young's Modulus over time of sample at 2mm/s. The gray lines represent the slope of the linear regime for any given cycle, while the orange line takes an average over 41 cycles. The Young's Modulus increases throughout cycling

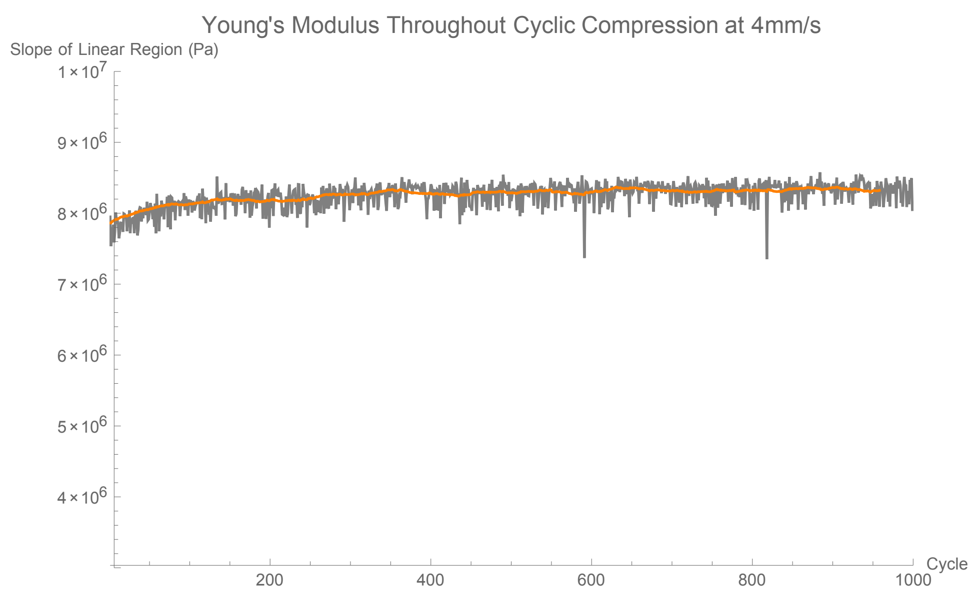

Figure 8: Young's Modulus time of sample at 4mm/s. The gray lines represent the slope of the linear regime for any given cycle, while the orange line takes an average over 41 cycles. The Young's Modulus increases slightly at the beginning, and later plateaus

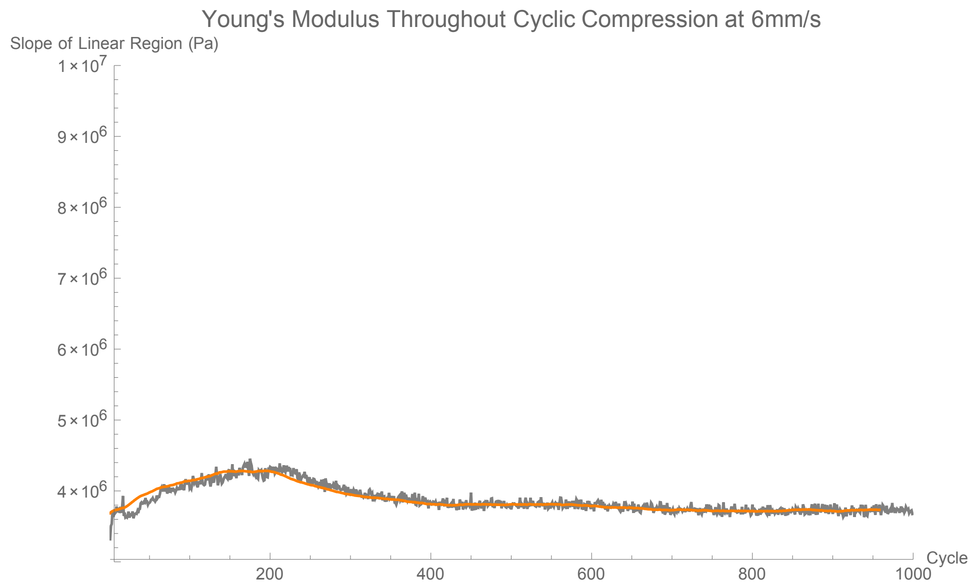

Figure 9: Young's Modulus over time of the second sample tested at 4mm/s. The gray lines represent the slope of the linear regime for any given cycle, while the orange line takes an average over 41 cycles. The Young's Modulus increases towards the beginning, but seems to decrease and plateau starting around 200 cycles

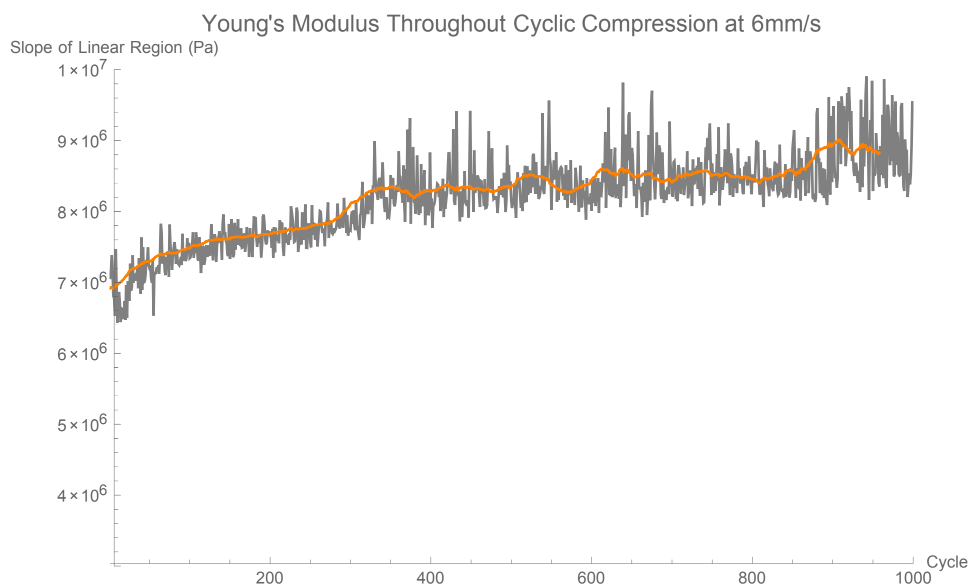

Figure 10: Young's Modulus over time of sample at 6mm/s. The gray lines represent the slope of the linear regime for any given cycle, while the orange line takes an average over 41 cycles. The Young's Modulus increases throughout cycling

5.3 Ballerina Testing

Multiple trials were conducted to test the force on the hallux using the polyurethane insert. As all three graphs were extremely similar, only one is placed in the results section. To compare the graph with other trials, as well as data from previous research, please see the appendix.

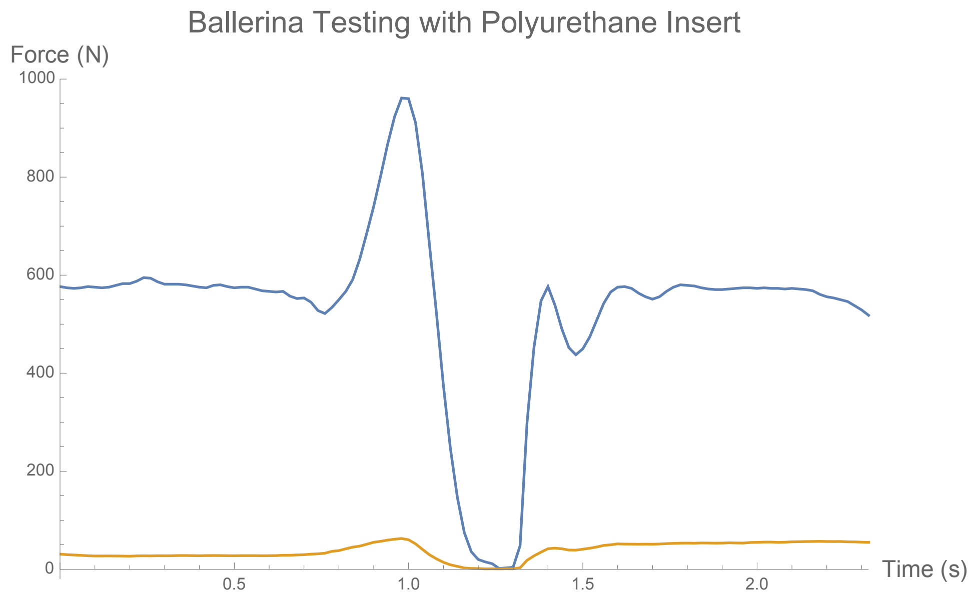

Figure 11: Ballerina test with polyurethane insert. The blue line represents the total body weight felt by the force plate, while the gold line represents the force on the big toe. The first peak represents takeoff, when she pushes off from demi-pointe, and the second represents her landing en pointe. Forces are taken at landing.

Shoe Type	F_{body} at landing (N)	F_{toe} at landing (N)	% Body on Toe
Unmodified	700	485	69.3%
Epoxy	850	150	17.6%
Polyurethane	562	22	3.9%

Table 3: Comparison of maximum force on hallux as percentage of body weight. Values for the unmodified and epoxy shoe are taken from the second of two jumps that the ballerina made.[8]

The ballerina also provided qualitative feedback regarding the inserts themselves. Since she had previously been fitted with the epoxy modification, she was able to discuss the differences between the two approaches, as well as which worked best. Though the ballerina said that the current fitting method for the polyurethane was messy, she had a positive opinion overall.

Quality	Epoxy	Polyurethane
Feel of floor	Retained	Retained
Comfort around bunion area and hallux	Increased comfort relative to unmodified shoe	No significant difference around bunion compared to unmodified shoe
Pressure en pointe	Reduced	Reduced
Preparation time	Acceptable	Acceptable
Cleanliness of fitting process	Extremely messy	Extremely messy once plastic broke
Comfort of fitting process	Very uncomfortable due to heating	Comfortable other than plastic sleeve itself

Table 4: Ballerina feedback (inserts). The ballerina provided feedback for both epoxy and polyurethane inserts when she was fitted for them. Her comments pertain to both the fitting process, and comfort of the insert itself

Analysis and Discussion

6.1 Ballerina Feedback

The qualitative feedback regarding the polymer slabs highlighted the importance of feel of the floor to the ballerina. She believed that the 40A slabs were too soft, complaining that they interfered with both balance and feel of the floor. Though she felt that they absorbed a good deal of shock and helped soften her landing, 40A polymers would not be adequate. In contrast, the 80A slab allowed perfect feel of the floor- the ballerina said there was no difference whatsoever. For this reason, it was expected that she would approve most of the 80A slab. However, this shore hardness was so stiff, that the ballerina said it was not comfortable. The 50A and 60A polymers produced an excellent balance between the two considerations: they were soft enough to increase comfort and absorb energy, but stiff enough that the ballerina was able to maintain balance.

Based on the ballerina's qualitative assessment, the decision was made to proceed with polyurethanes with shore hardness of 60A. Even though the ballerina felt the silicone slabs to be more shock absorbent than the polyurethane ones, the decision was made to proceed with polyurethanes in order to exploit the greater number of available options. Because of the toxic nature of the isocyanate component, Since there is a commercially available polyurethane of 60A shore hardness, this was selected as the best option.

During fitting, the dancer complained about the messiness of the process, which she claimed was worse than the epoxy modification. This occurred because the plastic wrap was stretched too tautly across her foot, so it was already under tension. It is possible that an untrimmed toenail could have punctured the wrap, but unlikely because most ballerinas keep their toenails very short. Though the ballerina was not irritated by the polyurethane, this identifies plastic wrap as an unacceptable barrier. In response to this, a nitrile glove was cut up. Equal amounts of A and B components were poured in, and the unsealed end of the finger was closed up with a length of wire. Though she did not mold such an insert to her foot, the ballerina thought that this would make a much better insert, as the nitrile is tougher and impermeable (the very reason it is used in gloves). The other main complaint was with regard to the tightness of the shoe. This can be resolved by using slightly smaller amounts of A and B.

6.2 Mechanical Testing

As expected, the polyurethane samples behaved more stiffly as the strain rate was increased. However, the samples tested at 4 mm/s were very different. The first sample tested at 4mm/s was much stiffer than the others. One reason for this might be that the samples tested at 2 mm/s and 6 mm/s had been made using the nitrile glove (still attached), while the sample tested at 4 mm/s had been made in a paper cup. When creating samples, the two components were mixed quite vigorously, which would have created air bubbles. Since there was no place for the air to escape from the nitrile glove, the samples made in the glove were more porous or foamy, while the sample from the cup was much more dense (see Table 2). One would expect the Young's Modulus to decrease with increased porosity, so this behavior makes sense.

The shock absorption followed a similar trend. The calculations for energy absorption were not done for a specific strain- rather, they were calculated for a load of 700N. This was done because a dancer going up en pointe will always apply the same weight to her toes, but may do so at different rates. Once again, the 4 mm/s samples did not fit in with the predictions. Since the Young's Modulus was so high in the first one, the sample would reach 700N at a very low strain, resulting in significantly lower energy absorption. This is consistent with the qualitative feedback given by the ballerina regarding the polymer slabs- stiffer ones felt like they absorbed a smaller amount of energy.

The Young's Modulus increased as samples were compressed for additional cycles. Although there was much variation from one cycle to the next, there was a clear trend overall. This trend was consistent even for the first 4 mm/s sample, which was an outlier for other data. However, there were some interesting differences in the shapes of the two graphs (Figures 8-10). The more porous samples, tested at 2 mm/s and 6 mm/s, simply seemed to increase, while the denser sample (4 mm/s) had an initial increase followed by a plateau. The increase in Young's Modulus is most likely due to densification of the sample. Once the sample is as dense as possible, it deforms according to a much more consistent Young's Modulus and the graph plateaus. The first 4 mm/s trial, since it was significantly denser to begin with, underwent a more rapid densification; for that reason, we can see the plateau in our results.

The second sample tested at 4 mm/s recorded very strange behavior- the Young's Modulus originally increased and then very quickly dropped back down. However, the Young's Modulus was in the same range as the other samples prepared in gloves. The sample's behavior most likely resulted from movement of the sample on the platen, which was not watched the entire time. Rather, the sample was secured to the lower platen with a length of tape, which had become unstuck by the end of the test. If the sample became misaligned, the area over which the load was applied would have been smaller, so the calculations would have been off. If the sample had not been misaligned, it is likely that the recorded Young's Modulus would have increased further, following a similar trend as the 6 mm/s sample.

The results from the hopping test recorded much lower forces on the hallux than a traditional pointe shoe, or even one with the epoxy modification. The epoxy modification done as previous research was excellent proof that an improved fit would result in a better weight distribution, but epoxy does not absorb much energy. The polyurethane inserts did a much better job of dissipating the forces while en pointe, resulting in a pressure on the toe that was almost indistinguishable from the forces while on the demi-pointe position. These results were so shocking that multiple trials had to be run with different force sensors, to ensure that it was not an equipment problem. However, they indicate that moldable polyurethane inserts do a phenomenal job of reducing pressure on the foot, through improved weight distribution and force dissipation.

Conclusion and Future Work

In conclusion, polyurethane inserts have the potential to be of great aid to dancers who go on pointe. These inserts decrease the pressure on the big toe, allowing for reduced pain and increased comfort while en pointe. This is because the inserts improve the overall fit around the toes, redistributing the weight. In addition they provide some energy absorption, which decreases the force applied to the foot. While the inserts do not do much for bunion relief, they prevent the phalanges, non-load-bearing bones by nature, from taking on 80% of a dancer's body weight. These inserts also provide a way for ballet to embrace more modern equipment for dancers- the traditional pointe shoe-making process is viewed as an art, so attempting to alter or replace it would be non-ideal. These inserts complement the rudimentary materials used in making pointe shoes, eliminating the need for the traditional break-in process and allowing the toe box to last longer (since pointe shoes are very expensive, this will help reduce lifetime cost for ballerinas). In addition, these inserts will preserve the aesthetic nature of ballet, something which prior pointe shoe modifications have been unable to achieve.

Because of the differences in the polyurethane samples, it is advisable to test a denser sample at 2 and 6 mm/s, as well as a nitrile-pouch sample at 4 mm/s. This would aid in understanding exactly why the 4 mm/s sample tested in this project provided results so different from what was expected. Additionally, one could run cyclic compression on polyurethane samples until failure; this would provide an accurate lifetime for the inserts.

One of the greatest opportunities for advancement is the creation of a marketable product, to actually use this research in order to help ballerinas. The use of the nitrile glove resulted in a tough, impermeable barrier that reduced the messiness associated with setting and curing polyurethane. However, the hardest part would be to separate both components until such time that they need to be mixed- part A needs to be kept in one side, and part B in the other. One way to do this might be to have a clamp in the center of the pouch, keeping them completely separate until such time that the insert needs to be molded to the dancer's foot.

Another consideration would be the use of two-part silicone, rather than polyurethane. Cured polyurethanes are non-toxic, and even after 1000 cycles of compression samples did not show significant wear. However, there is a hazard associated with isocyanates, a critical component in producing polyurethanes. Though ballerinas would not be expected to go through too many inserts (likely one every few months or so) and the product would be designed not to leak, accidents are always possible. Therefore, a non-toxic interior would be of benefit.

These two points would provide ample improvements to the inserts, developing the concept into a product without modifying its performance.

Appendix

8.1 Cyclic Compression

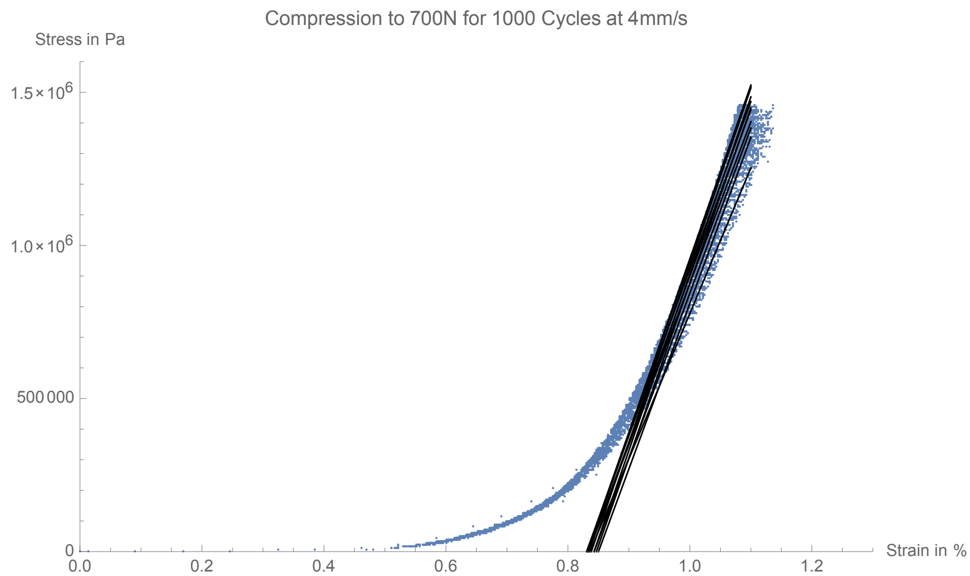

Figure 12: Loading curves to 700N for 1000 cycles at 2mm/s

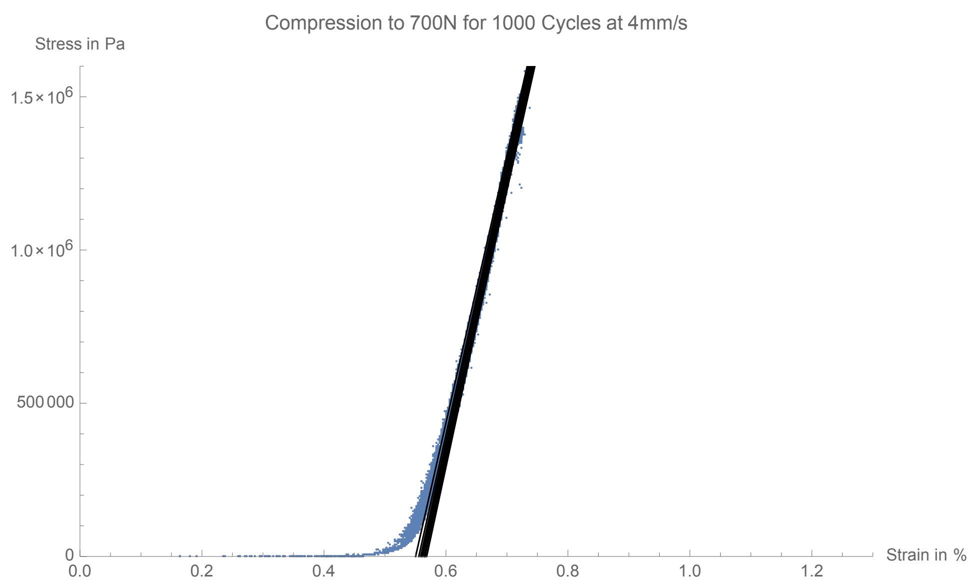

Figure 13: Loading curves to 700N for 1000 cycles at 4mm/s (first sample)

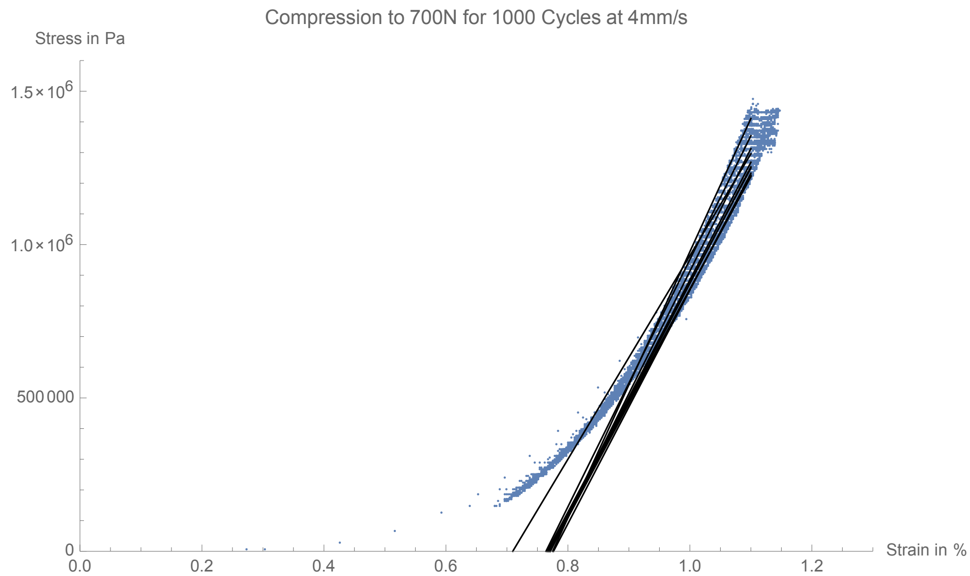

Figure 14: Loading curves to 700N for 1000 cycles at 4mm/s (second sample)

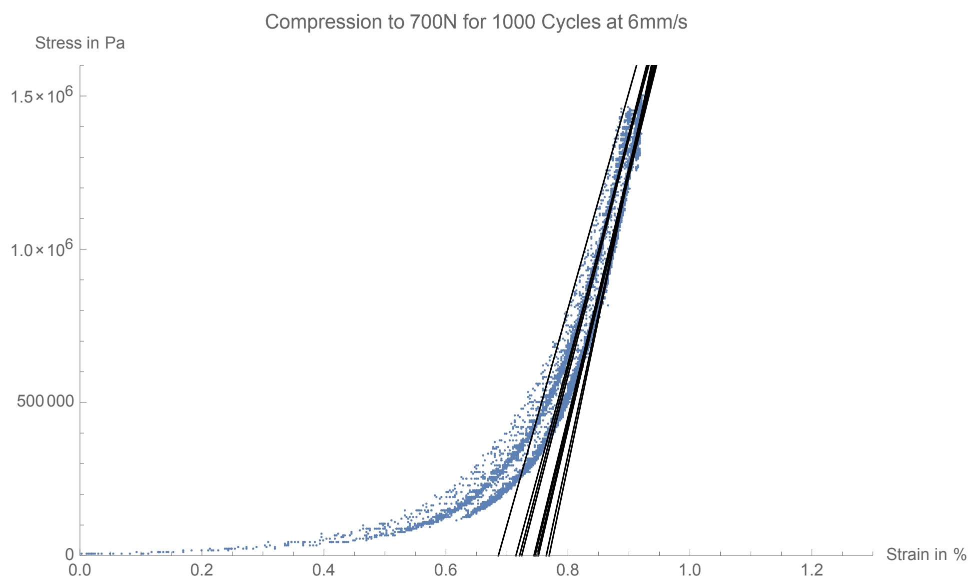

Figure 15: Loading curves to 700N for 1000 cycles at 6mm/s

8.2 Mathematica Program

8.2.1 Functions Used

```
(*function that pulls out all the relaxations in the graph*)
(*if it's smaller than before, ignores it*)
newgraph[mygraph_] :=
 Module[{new = {mygraph[[1]]}, i, len = Length[mygraph]},
  For[i = 2, i < 25, i = i + 5,
   If[mygraph[[i, 2]] ≥ mygraph[[i - 1, 2]],
    new = Append[new, mygraph[[i]]]
   ]
  ];
  For[i = 11, i < len, i = i + 5,
   If[mygraph[[i, 1]] ≥ mygraph[[i - 20, 1]],
    new = Append[new, mygraph[[i]]];
   ]
  ];
  new
 ]

(*function to take newgraph and refine now that it's much smaller*)
(*works just like newgraph but i+=1 not 5*)
refine[mygraph_] :=
 Module[{new = {mygraph[[1]]}, i, len = Length[mygraph]},
  For[i = 2, i < len, i++,
   If[mygraph[[i, 1]] ≥ mygraph[[i - 1, 1]],
    new = Append[new, mygraph[[i]]];
   ]
  ];
  new
 ]

(*function to take linear regions --> young's modulus*)
(*when there's a drop, take linear region beforehand*)
getlines[mygraph_] :=
 Module[{new, i, len = Length[mygraph], linfit, lines = {{"slope", "inter"}}},
  For[i = 3, i < len, i++,
   If[mygraph[[i, 1]] ≤ mygraph[[i - 1, 1]],
    new = mygraph[[i - 10 ;; i - 1]];
    linfit = FindFit[new, a * x + b, {a, b}, x];
    lines = Append[lines, {linfit[[1, 2]], linfit[[2, 2]]}];
   ]
  ];
  lines
 ]

(*function to get absorption*)
shock[mygraph_] :=
 Module[{energy = 0, i, len = Length[mygraph], old = 1, area},
  For[i = 2, i < len, i++,
   If[mygraph[[i, 1]] ≤ mygraph[[i - 1, 1]],
    area =
     Integrate[Interpolation[mygraph[[old ;; i - 1]]][x], {x, mygraph[[old, 1]], mygraph[[i - 1, 1]]}];
    energy = energy + area;
    old = i;
   ]
  ];
  energy
 ]
```

```
(*function to average out modulus values and reduce noise, takes in a "lines" table*)
noise[mygraph_] :=
 Module[{noiseless = {}, avg, i, len = Length[mygraph]},
  For[i = 21, i < len - 20, i++,
   avg = Total[mygraph[[i - 20 ;; i + 20, 1]]] / 41;
   noiseless = Append[noiseless, avg];
  ];
  noiseless
 ]

(*function to get stopping point for first curve (cyclic)*)
stop[mygraph_] :=
 Module[{part, i = 2, len = Length[mygraph]},
  While[mygraph[[i, 1]] ≥ mygraph[[i - 1, 1]], i++];
  part = mygraph[[1 ;; i]]
 ]

(*function to get absorption under first curve (cyclic)*)
shock[mygraph_] := Integrate[Interpolation[mygraph][x], {x, mygraph[[1, 1]], mygraph[[-1, 1]]}]

(*function to get the slope of first curve (cyclic)*)
getoneline[mygraph_] :=
 Module[{sloped, len = Length[mygraph], linfit},
  sloped = mygraph[[len - 10 ;; len]];
  linfit = FindFit[sloped, a * x + b, {a, b}, x]
 ]
```

8.2.2 Analysis of Data

```
(*REFINE DATA*)
(*import file*)
table = Import["Desktop/Thesis/sample2.csv"];
table = table // Transpose; (*row 1 is load, row 2 is compressive extension*)
table[[1]] = -table[[1]];
(*load is now positive*)

(*calculate stress*)
load = table[[1, 3 ;; -1]];
area = 0.0125^2 * Pi; (*diam is 2.5cm, give r in m*)
stress = load / area;

(*calculate load in lbs*)
newtonlbs = (1 / 9.8) * (2.2);
loadinlbs = load * newtonlbs;

(*calculate strain*)
ext = table[[2, 3 ;; -1]];
thickness = 6.5; (*in mm*)
strain = (ext) / thickness;

(*combine and set a new start point when 2N of force are present*)
mydata = {strain, stress};
mydata = mydata // Transpose;

(*refine data*)
uponly = newgraph[mydata];
step2 = refine[uponly];
step3 = refine[step2];
final = refine[step3];
```

```
(*PAST REFINING DATA*)
(*take linear regimes/slopes*)
myline = getlines[final];
(*average young's modulus*)
Total[myline[[2 ;; -1, 1]]] / 1000
(*track change over time/trends*)
track = noise[myline[[2 ;; -1]]];
(*make into equations*)
lines = a * x + b /. {a → myline[[2 ;; -1, 1]], b → myline[[2 ;; -1, 2]]};

(*PAST REFINING DATA*)
(*get the first cycle*)
once = stop[final];
(*get its information*)
getoneline[once]
shock[once] / 1000

(*PLOT*)
fplot =
  ListPlot[final, AxesLabel → {"Strain in %", "Stress in Pa"}, PlotRange → {{0, 1.3}, {-1, 1.6 * 10^6}},
   PlotLabel → "Compression to 700N for 1000 Cycles at 4mm/s", ImageSize → Large];

eyplot = ListLinePlot[myline[[2 ;; -1, 1]], PlotStyle → Gray,
   AxesLabel → {"Cycle", "Slope of Linear Region (Pa)"}, PlotRange → {{1, 1000}, {3 * 10^6, 1 * 10^7}},
   PlotLabel → Style["Young's Modulus Throughout Cyclic Compression at 2mm/s", FontSize → 14],
   ImageSize → Large];

noiseplot =
  ListLinePlot[track, PlotStyle → Orange, AxesLabel → {"Cycle", "Slope of Linear Region (Pa)"},
   PlotLabel → "Young's Modulus Throughout Cyclic Compression at 2mm/s", ImageSize → Large];

linplot = Plot[lines[[{1, 100, 200, 300, 400, 500, 600, 700, 800, 900, -1}]],
   {x, 0, 1.1}, PlotStyle → {Black, Thickness[0.002]},
   AxesLabel → {"Strain in %", "Stress in Pa"}, PlotRange → {{0, 1.1}, {-1, 1.6 * 10^6}},
   PlotLabel → "Compression to 700N for 1000 Cycles at 2mm/s", ImageSize → Large];

Show[eyplot, noiseplot]
Show[fplot, linplot]
```

8.3 Data from Impulse Test with Ballerina

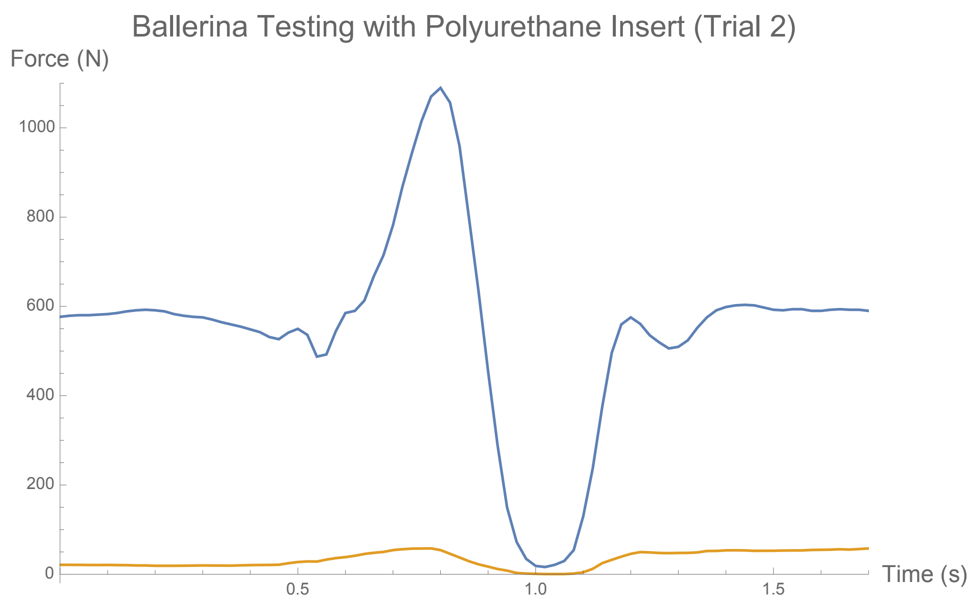

Figure 16: Ballerina test with polyurethane insert, trial 2

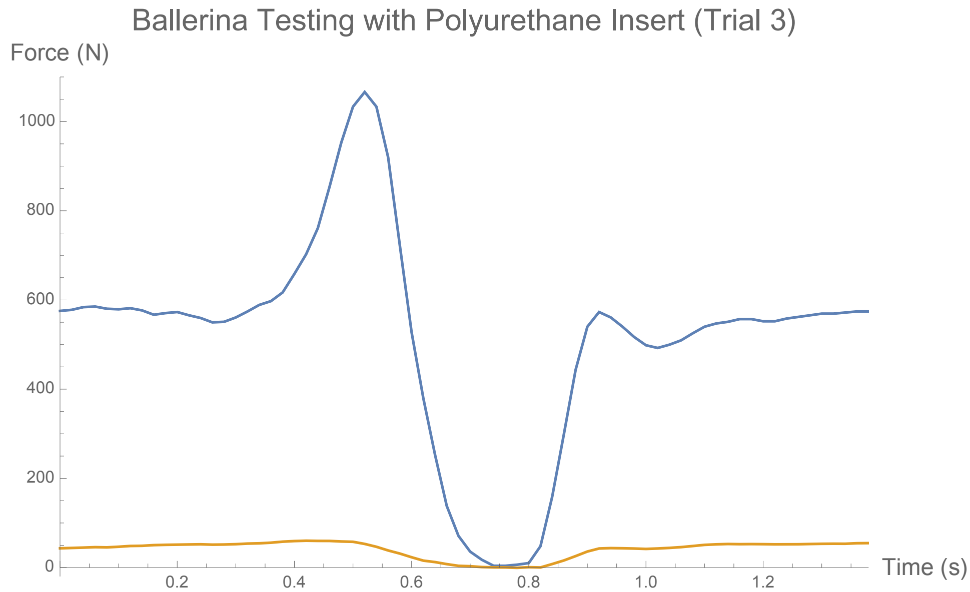

Figure 17: Ballerina test with polyurethane insert, trial 3

8.3 Ballerina Data from Literature

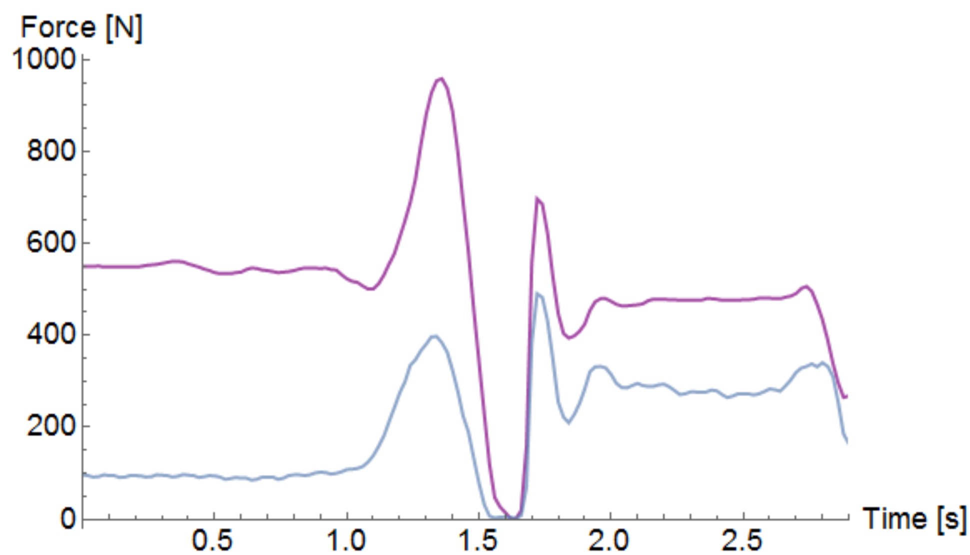

Figure: Ballerina testing with a new, unmodified shoe. The first peak marks the beginning of the jump, while the second peak marks the landing onto pointe.[8]

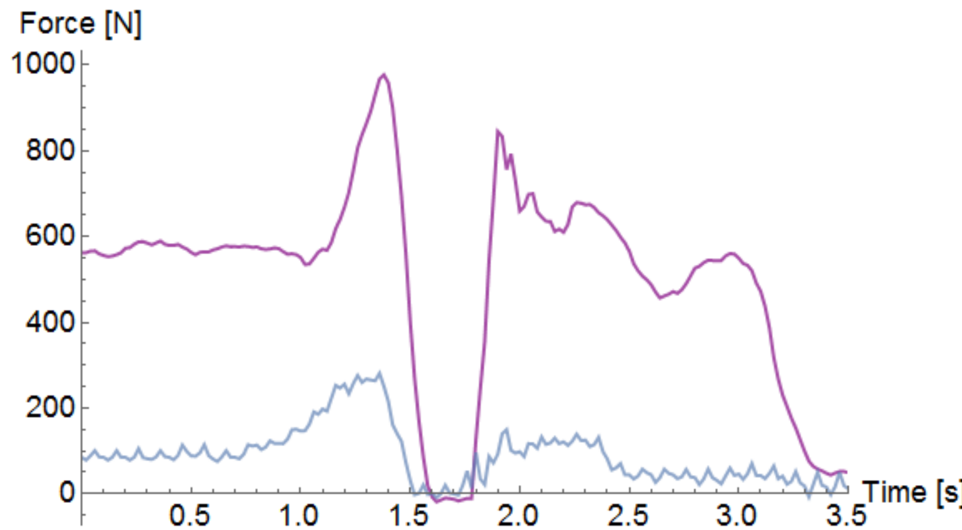

Figure: Ballerina testing with a shoe containing an epoxy modification. The first peak marks the beginning of the jump, while the second peak marks the landing onto pointe[8]

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