Unconventional Sneaker Design:

The Design and Exploration of a Bamboo Spring-Actuated Running Shoe

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Abstract

The impetus for this thesis was to engineer, design, and fabricate a running shoe whose primary mechanism of shock absorption in the sole was a cantilever spring made of wood and/or a woody material. While modern sneakers boast an impressive breadth of shapes, colors, and well-marketed sole technologies across different models and brands, they are manufactured using a rather rigidly-defined arsenal of synthetic plastic-based fabrics and foams. With that said, the author wanted to explore how the design of a sneaker would change if it were instead made of wood and other naturally-derived materials.

The primary investigation was to see if a sneaker comprised of sustainable and environmentally-friendly components would be able to match or even exceed the performance of plastics-based running shoes that have become the standard. Aesthetics were also an important consideration for the final product.

Through research and analysis of the material properties belonging to different types of wood, it was decided that bamboo would be used for the sole due to its high strength-to-weight ratio, sustainability (fast growth rate), and unique appearance. Other materials included cork, hemp fabric, and hemp twine for the various other parts of the shoe.

Two iterations of design were completed, with issues and complications from the first improved upon in the second. It was determined that a durable and comfortable shoe made from bamboo is highly feasible, and that the cantilever spring sole is both mechanically effective and aesthetically unique. Due to natural variability in organic materials like bamboo, production consistent with design intent was difficult to achieve and manufacturing defects that affected the characteristics of the heel spring were present. Therefore, results may not reflect the potential of the design and materials under more ideal conditions.

Remedies and future improvements are proposed. Ultimately, much insight was gained into finding a new way of manipulating one of mankind's most ubiquitously-used materials.

Acknowledgements

This thesis could not have been completed without the guidance and help of many people. First and foremost, I would like to thank my Mom and Dad for raising me to be the person I am today and for supporting me through thick and thin. Thank you to my dog Dexter for the uncanny ability to always cheer me up and for all the silly things you do. Thank you Professor Lidow for that fateful introduction to design thinking after Tim Brown and Tom Kelley's talk in McCosh 50, and of course for advising my thesis and encouraging me to pursue my zany ideas. Thank you Professor Nosenchuck for providing much insight into the world of possibilities that is mechanical engineering, and for being the reader of this thesis.

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To my family, creativity, and the perennial pursuit of creating awesome things.

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Chapter 1

Introduction

1.1 History of Footwear

1.1.1 History of Running Shoe Technology

Humankind and footwear have an intimate relationship. For most people, putting on a pair of shoes is beyond an afterthought in the morning before heading out for a day's work. This object, so easily taken for granted and left to our unconscious mind, is however an indispensable engineering feat that has been in development over the course of human history. In the year 2016, a myriad of personal gadgets and gizmos aimed towards easing human locomotion have become commonplace, from Segways to electric skateboards. Despite this list of impressive tech toys, they are far from replacing the standard of movement, one that has been with us since day one: walking, and its hastier cousin, running. To that end, the need to protect one's feet from the hazardous conditions of this world has been timeless. Over the course of millennia, humans have looked to crafting footwear as the solution.

In 1938, the oldest footwear known in existence was discovered by Luther Cressman, an anthropologist and archaeologist working in Central Oregon [1]. From within Fort Rock Cave came a pair of 10,000 year-old braided sagebrush bark sandals, with a tightly woven outsole and straps that secured it to the wearer's foot [2]. Although the design is crude and primitive in modern standards, the sandals discovered by Cressman are an example of mankind's early attempt to improve mobility.

Fast-forwarding several thousand years, footwear has already branched into a multitude of unique varieties among ancient civilizations. The Greeks, for example, de-

Figure 1.1: 10,000 year-old Fort Rock Cave sandals [3]

veloped race sandals known as *ligula* to improve traction during running [1]. Ancient Romans developed many styles of footwear, including the distinguishable *caligae*, a type of strapped military boot made of leather that has been curiously resurrected as fashionable women's wear in modernity.

Another article of footwear from antiquity whose modern rendition is enjoying success as a fashion staple is the moccasin. The moccasin, in its original form, encompasses a wide range of footwear worn by the indigenous peoples of North America. Most commonly, it refers to soft slipper-like shoes made of deer, elk, or buffalo leather made for protection from the elements [4]. However, the term "moccasin" also refers to sandals made of vegetable fibers made by tribes in warmer climates, just like the Fort Rock sandals as seen in Figure 1.1 and other groups from further south. Of the latter are the Tarahumara Indians who reside around the canyons of northern Mexico's Sierra Madre Occidental mountain range. The Tarahumara are particularly noteworthy because of their prowess in endurance running. In fact, their name for themselves, Rarárumi, means "he who walks well" [5]. Claims state that the Tarahumara have easily outrun highly-trained Americans in ultramarathons, the feat being made ever more impressive given the Tarahumara's lack of consistent training and taste for junk food. Rather, they engage in an ancient relay race and ball game hybrid, where teams kick a ball while running distances upwards of 75 kilometers, several times a year [6].

Looking at the feet of the Tarahumara may also warrant some surprise at their athleticism. This is because of the *huaraches*, or running sandals, that they wear. *Huaraches* are traditionally made from nothing more than a thin piece of leather that

Figure 1.2: Modern *huaraches* worn by a Tarahumara Indian [8]

acts as the sole, creating an unintrusive barrier between the wearer's feet and the ground. The leather sole is laced around the foot and ankle with thin straps made of more leather or plant-based fibers. Modern *huaraches* boast a similar design but with synthetic materials like rubber soles repurposed from old car tires and straps made of nylon rope. Non-Tarahumaran runners looking for a minimalistic experience often look towards *huarache*-style sandals made by certain companies [6]. The ability for Tarahumara runners to perform so well in such barebones — and what some might call "low tech" — footwear has been a point of both scientific research and popular debate [6][7].

The advent of the conventional running shoe as we know it today began in the 17th and 18th centuries in Britain. Spiked athletic shoes were developed for cricket. In 1861, the Spencer cricket shoe came into existence with a four-spike construction, three under the forefoot and one under the heel [2]. Track became a popular sport in the late 1800s, and a similar spiked design was incorporated into running shoes made of lightweight kangaroo leather. It was around this time that rubber, then a novel and exotic material to most Western civilizations, was augmented into a durable advancement for shoe technology due in part by a man named Charles Goodyear [1].

Before Goodyear's time, rubber in its natural form, or latex, was a fickle substance. Its elasticity changed dramatically depending on the temperature, going from soft and sticky in the heat to hard and brittle in the cold [1]. This was a glaring limitation that prevented latex from being implemented into an object that had to endure the wear and tear of prolonged, high-force movement in an outdoor environment. As the story goes, Goodyear was an inventor steadfast on finding a way to "cure" rubber's temperamental characteristics. On a fortuitous occasion, Goodyear decided to try adding sulfur to rubber, and after accidental contact with a hot stove, the test sample was found to possess a leathery quality without any of the problematic stickiness [1]. This marked an early foray into the process now known as vulcanization, which transformed the rubber industry into an indispensable part of modern society.

Vulcanization acted as a springboard for the shoe industry. British and US companies began manufacturing rubber-soled shoes with cloth and leather uppers. These were the first sneakers, or plimsolls as they were known in Britain [1]. Many of the big names in running shoes today have their roots at this critical juncture around the turn of the 20th century. Among these names is Reebok, started as a small shoe business called J. W. Foster and Sons Limited by the eponymous Joseph William Foster in 1895 in the United Kingdom [2]. Foster's grandsons would eventually go on to leave their grandfather's business and start Reebok in 1958. Perhaps one of Reebok's most recognizable contributions to the running shoe, and shoes of other sports in general such as basketball, was the Pump, an air bladder inside the tongue of the shoe that inflated when the wearer squeezed a mechanism, creating a customized, tight hold around the ankle [2].

Other companies include the Riley Company, founded by William J. Riley in 1906, which was the predecessor to New Balance. The German Dassler brothers, Adolf and Rudolph, began making shoes in 1920 and even later supplied athletes in the 1936 Munich Olympics such as Jesse Owens [2]. In 1948, the brothers split, with Adolf going on to establish Adidas and Rudolph founding Puma, Adidas' long-time rival. Adolf used arch support lacing and adopted three stripes around the midfoot to create added support [2].

Arguably one of the largest mainstays of the footwear industry is none other than Nike. Founded by track athlete Phil Knight and his University of Oregon coach Bill Bowerman in 1964, Nike had a rather humble beginning as Blue Ribbon Sports. Knight and Bowerman's small company was a distributor and collaborator with Onitsuka Tiger (now known as ASICS), itself started 15 years prior in Japan [2]. In 1967, Blue Ribbon Sports released the Tiger Marathon shoe, which featured a light rubber outsole and a heel and forepart crafted from different pieces. 1972 marked a major turning point for Knight and Bowerman. This was the year in which they separated from Onitsuka Tiger over distribution disputes and formed Nike as it is today [2]. With a new, iconic "Swoosh" logo, Nike began to pave its way towards absolute suc-

Figure 1.3: Nike Waffle Trainer, 1974 [9]

cess. When the '70s approached, further advancements in running shoe technology would enable designs that started to resemble running shoes as they are known today.

One major milestone in technology was the introduction of a new material into the sole to help with shock attenuation. In 1974, The Brooks Company president Jerry Turner brought in a chemical engineer who introduced a promising elastomeric foam called ethylene vinyl acetate, or EVA [2]. Air bubbles formed by a blowing agent during production are encapsulated within the material, creating what is known as closed-cell foam. The air bubbles made EVA a superior sole material to the solid rubber that had been prevalent in shoes until then in multiple ways. For one, the existence of air within the EVA foam made the material far less dense, thereby decreasing the overall weight of the shoe [2]. The air bubbles also offered better compression characteristics. Under force, the cell walls would deform, absorbing energy from the wearer as they struck the ground. Other running shoe companies would soon catch on to the groundbreaking material, like Nike did with the Waffle Trainer in 1974 (Figure 1.3). To this day, EVA is still used in midsoles for running shoes, its adjustable density and properties when mixed with other polymers owing to its continued success [2].

Further research and the establishment of the American Academy of Podiatric Sports Medicine in the early 1970s led to other advancements in shoe technology [2] in the late 20th century. Changes in footwear design, such as the addition of heel counters and wedged soles, added stability and comfort. Now in the 21st century, improvements to shoe design have yet to cease as companies both new and familiar continue to roll out more exciting products than ever. Please see Section 1.2 for more details on the different features of a conventional modern running shoe.

1.1.2 History of Wood and Plant-Based Materials in Footwear

People utilized the resources in the world around them, like plants, animals, and other organic[1] substances, to create different types of footwear before the advent of synthetic materials such as nylon, EVA foam, and other plastics. As already mentioned, indigenous peoples of North America made sandals out of sagebrush and *huaraches* with leather. Wood, despite its hardness and perceived lack of flexibility, was also surprisingly used to create common footwear in several different societies throughout history.

Figure 1.4: Various *geta* on display [10]

One such item was the *geta*, an umbrella term referring to multiple types of traditional wooden sandals originating in Japan. *Geta* were developed at the end of the 8th century and boasted a peculiar yet functional feature: one or more stilt-like wooden blocks under each foot [11]. These blocks essentially turned the *geta* into platform shoes that were raised high above the ground, keeping the wearer's feet and *kimono* protected from the ground. Originally worn only by people of elite status such as priests and the emperor himself, *geta* eventually made its way onto the feet of commoners by the Edo period by the 17th century. Various styles with stilts of differing quantities and sizes were developed for specific purposes. For example,

[1]For the sake of this thesis, the term "organic" will refer to the broad category of materials derived from nature and minimally processed.

takaba geta with very high blocks were intended for use in the rain, while *chakkiri geta* were developed to cut tea leaves [11]. To this day, *geta* are still worn on special occasions and by certain occupations, such as sumo wrestlers and sushi chefs.

In Europe, wooden footwear took the form of the clog. Clogs, like *geta*, came in different shapes depending on the region they were made in, but perhaps the most "notorious" of clogs were the ones carved from a single block of wood with a hole for the feet. These include the Dutch *klomp* and French *sabot*.[2] Beginning around the 12th century, European peasants began wearing clogs to keep their feet clean while working in the fields. Made from woods such as birch, willow, and alder, clogs' durability and versatility lent to their adoption later on by industrial factory workers and elites alike [11].

Other types of clogs were constructed from pieces of wood held to the bottom of the foot by leather straps. These were primarily worn by European elites by the 14th century as an overshoe that kept shoes made from cloth or leather clean in an outdoor environment. These include galoshes, pattens, and chopines, all of which were elevated with the same purpose in mind as *geta* [11]. Chopines also served as a status symbol for women, their height directly correlating with the prominence of the wearer. Women wearing especially tall chopines naturally found it difficult to move, but their wealth allowed them servants that assisted in walking.

The abundance of wood as a natural resource and its ability to take a beating made it an easy choice of material for footwear all around the world throughout history. Despite their prevalence and significant use, wooden shoes were largely developed for specialized tasks, be it for agricultural work or flaunting one's wealth. They were never designed to enable speed and dynamic footwork. The rigidity and structural strength of wood has allowed it to flourish as an essential component of objects like buildings and furniture, but these properties quickly became a disadvantage towards the natural flexibility and moving contours of the human foot. As such, it can be surmised that footwear (e.g. moccasins, straw sandals, etc.) made from more pliable but less robust materials, like leather and plant fibers, instead filled the role of protecting feet when the wearer needed increased mobility.

[2]Fun fact: It is said that French factory workers in the 19th century threw their clogs into the mills during strikes to cause disruption, leading to the origin of the word "sabotage."

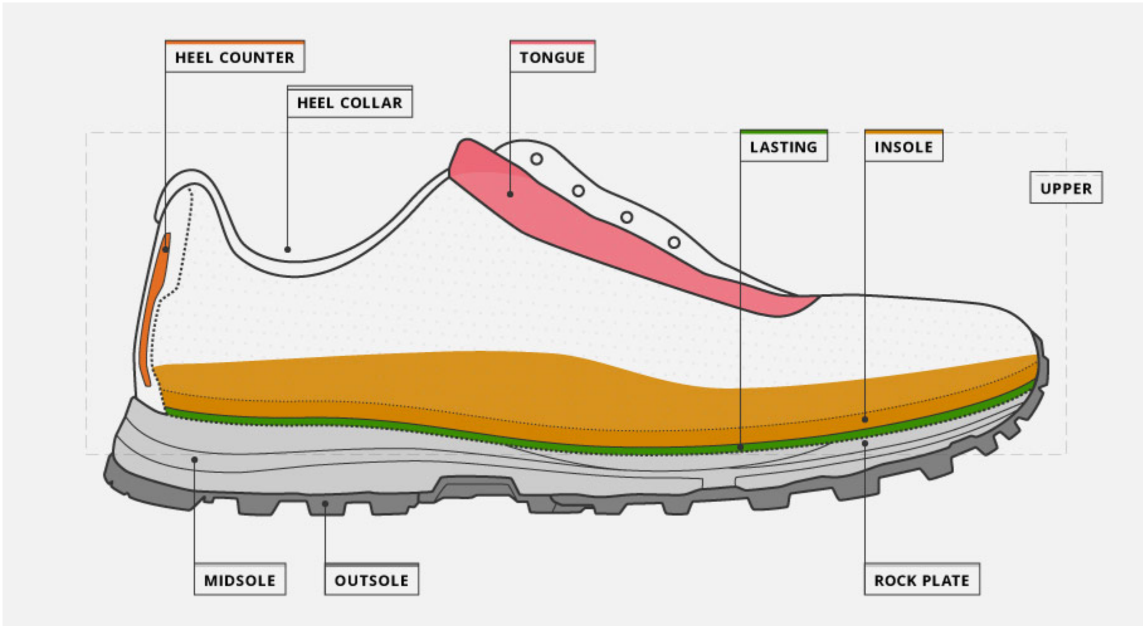

Figure 1.5: Running shoe anatomy [12]

1.2 Conventional Modern Running Shoe Design

Despite the seemingly endless number of brands and models offered to consumers, most modern running shoes and their features follow a standard layout as outlined in Figure 1.5. The major components of a running shoe are the **outsole**, **midsole**, **insole**, and **upper** (which encompasses everything above the insole including the tongue, vamp, toe box, tongue, and **heel counter**).

Outsole

The outsole of the shoe directly interfaces with the ground. Its job is to provide traction and protection from hazardous debris on the ground. However, the outsole needs to remain flexible as it cannot restrict the rest of the shoe from bending with the foot's motion. As such, vulcanized natural rubber and synthetic elastomers such as ethylene propylene diene monomer (EPDM) and thermoplastic polyurethane (TPU) are common choices of material due to their high coefficients of friction, good wear resistance, and flexibility [13]. These elastomers can also be injection-molded to form complex grooves and patterns to assist with traction.

Midsole

One of the areas of running footwear that has seen the most focus in terms of research and marketing is the midsole. This is the part of the shoe that provides shock absorption and the cushion that can make or break a particular shoe's comfort. In addition, the midsole provides varying degrees of stability when the foot lands depending on the type of material or mechanism used. Therefore, there is always a balance between cushion and stability. Running shoe companies have taken advantage of this by creating different models catered towards runners looking for a softer ride, better control, or a happy medium.

The most common midsole mechanism is a simple layer, or layers, of foam that compress underneath the foot. As mentioned before, EVA (including its many variations) is the industry standard for midsole foam [2]. By changing additives and other formulation parameters, EVA foam can take on a whole spectrum of densities and compressive strengths. For example, Nike's Lunarlon cushioning is a blend of nitrile rubber and EVA [14]. Other proprietary EVA blends include Mizuno's U4iC, New Balance Fresh Foam, and Saucony PowerGrid to name a few [14]. Another common foam is polyurethane foam, which is generally denser, less prone to compression set (or permanent deformation, like the foam going "flat"), and has a higher compression strength [13]. PU foam is typically used under areas of the foot that experience higher impact forces during running, such as the heel and the balls of the feet.

Other midsole mechanisms include Nike Zoom and plastic, mechanical springs in Adidas Springblade shoes. Zoom, one of Nike's flagship technologies that has been constantly iterated upon for several decades, is a pressurized air unit that works much like an air bag, compressing under load and attenuating shock [13]. The Adidas Springblade (discussed in more detail in Section 2.1 as a source of inspiration for this thesis) on the other hand is a shoe that relies not on the elastic nature of foam, but the deflection of plastic blades running underneath the foot to provide shock absorption. Other technologies by these and other brands also exist, but most midsoles, even ones featuring non-foam mechanisms like Zoom, incorporate foam in certain areas.

Insole

The insole of a shoe is located inside the upper and is what the foot rests directly on. Insoles provide additional cushioning and help to hold the foot in place so that it does not slide around inside the upper, potentially causing blisters on the dorsum of the foot [2]. Many insoles are also made of EVA as it conforms to the shape of the foot. Depending on the shoe, insoles can come as a permanently-glued fixture or as a separate, removable piece. Insoles of the latter kind can be replaced with both pre-fabricated or custom upgrades that cater to the anatomy of a particular person's foot [2].

Upper

Everything above the sole of a shoe can be considered a part of the upper. The upper as a whole provides the job of securing the foot to the sole as well as shielding the top of the foot from bumps and scrapes. The front portion of the upper is referred to as the vamp [2]. The tongue is a separated piece that provides padding against lacing and is generally overlapped by the sides of the upper, known as the quarter.

The materials the upper is made of are vital to how comfortable the shoe is. Historically, running shoes were made out of leather. However, leather has fallen out of favor due to its tendency to lose shape when wet, necessary routine maintenance, and lack of breathability compared to synthetic fabrics and meshes made out of nylon or polyester [2]. Advances in textile technology have also allowed for lighter, stronger, and thinner uppers that can have a second-skin-like feel. In addition, uppers, which are traditionally sewn from several pieces of stamped material, can now be spun directly into shape with varying knit densities. Nike, for example, introduced Flyknit to the footwear market in 2012. The company claims that the spun nature of the upper contributes to less waste material because pieces of leftover fabric typical of stamping processes are no longer present in manufacturing [15]. Flyknit can be adjusted at the thread level to vary density, rigidity, and breathability depending on which part of the upper is being made. For example, the heel section of the upper can be spun with more layers and a tighter weave to provide reinforcement and structure for both the shoe and the foot. The toe box, on the other hand, can be created with deliberate holes in the knit to encourage airflow.

Heel Counter

The heel counter is the final major component in most standard running shoes. As its name suggests, it is located at the rear of the shoe. The heel counter functions to enclose the wearer's heel in a stabilizing cage that mitigates ankle rotation, which can lead to injury. The walls of the heel counter hold the foot in an upright position and prevents the ankle from collapsing sideways. For some people, the ankle can be

Figure 1.6: Heel counter (upper left) as it would be placed in a shoe [13]

overrotated in neutral stance. This is called overpronation or oversupination depending on the direction in which the ankle is twisted (see Section 1.3 for more details) [2]. As such, more noticeable and rigid heel counters are used in running shoes made for helping unstable foot types and possessing more motion control [2].

In their most basic form, heel counters are simply plastic inserts hidden between layers of fabric in the upper. Figure 1.6 shows a heel counter in its location in the shoe without the rest of the upper present. Many shoes feature external heel counters that *are* visible and serve both supportive and cosmetic purposes.

Some specialized running shoes do not feature a heel counter altogether. These shoes are usually catered towards the minimalist running community that prefer to have as close to a barefoot experience as possible. Therefore, these minimalist running shoes generally lack major support in other areas as well. However, this makes them very light, soft, and flexible [2].

1.3 Biomechanics of the Foot

So why even wear shoes? Why do modern running shoes look the way they do? These questions can be answered by analyzing the biomechanics of the human foot.

Next to galloping horses, swinging chimpanzees, and our own pet cats and dogs, even the most athletic human beings pale in comparison in terms of raw strength, agility, and coordination. It may appear that *Homo sapiens'* place on Earth would be long gone had it not been for brainpower. However, research has shown that humans are surprisingly excellent in terms of endurance and aerobic capability [16]. In fact, endurance running is unique to humans among primates and is rarely observed outside of quadrupedal mammal species that are social carnivores or migratory ungulates [17]. A comparison between humans and horses shows just how remarkable our endurance is. The average endurance running (ER) speeds for a human being are between 2.3-6.5 m/s, with recreational joggers able to sustain speeds of 3.2-4.2 m/s [17]. These speeds match or even exceed the preferred trotting and trot-gallop transition speeds of ponies, which are 3.1 and 4.4 m/s respectively [17]. Over long distances, human ER speeds are comparable to the preferred galloping speed of a horse for longer than 10-15 minutes of running (5.8 m/s) and 100 kilogram Wildebeests (5.1 m/s). Of course, these mammals are far heavier than the average human being, but even the predicted ER speed of a 65-kg quadruped is less than the ER speed of fit humans [17].

Humans' ability to run is aided by the existence of multiple spring-like tendons in the legs [17]. One such tendon is the Achilles tendon, which is significantly longer in humans than in other primates [16]. Another is the plantar arch, located between the heel and the ball of the foot. The elastic nature of these tendons allows them to function as springs, storing energy from impact forces through compression and tension, and propelling the body forward by releasing it [17]. The plantar arch alone stores and releases approximately 17% of the energy generated by the foot impacting the ground [16].

The human feet alone appear to have evolved quite splendidly for the purpose of walking and running. Surely, hunters in prehistoric and ancient times without the luxury of EVA foam must have had no problem getting around in crude leather and plant-based footwear or even barefoot. As such, questions concerning the effectiveness and benefits of modern running shoes have been raised. Is all that foam really necessary? Are we perfectly capable of getting around sans-footwear? Looking at foot strike behavior between shod and barefoot runners may just yield the answer.

Much research has been performed by Daniel E. Lieberman et al. at Harvard University into the differences between running with and without shoes and their effects on how the foot lands on the ground [18]. It was found that most barefoot runners land with a front-foot strike (FFS), while 75-80% of shod runners land with a rear-foot strike (RFS) [18]. This change in behavior is due largely to the perceived comfort of each method of foot strike. In barefoot runners, landing on the rear-foot causes a high impact transient, a sudden force of large magnitude roughly **1.5 to 3 times the runner's body weight** that makes it way through the body and can

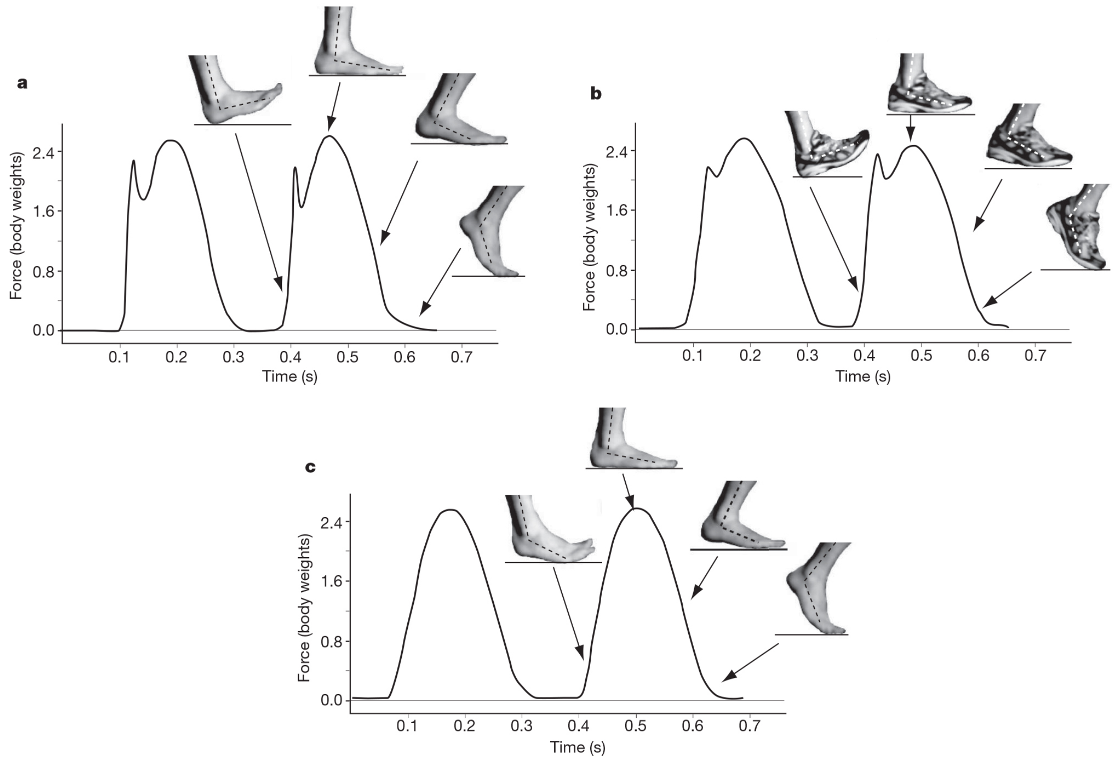

Figure 1.7: Barefoot RFS (a) vs. shod RFS (b) vs. barefoot FFS (c) impact forces normalized to body weight. Note the prominent spikes in (a) and (b) that correspond to the impact transient [18]

cause injuries [18]. However, this impact transient is inexistent during FFS in barefoot strikes (see Figure 1.7). FFS allows the linear downwards momentum produced during impact to translate into rotational momentum around the ankle as the foot dorsiflexes under control of the Achilles tendon and triceps surae muscles [18]. However, RFS occurs right under the heel, generating minimal torque around the ankle and causing the full force of impact to bear down nearly instantaneously. Therefore, it is far more comfortable to land on the fore-foot than the rear-foot when running without shoes.

The tendency for shod runners to RFS is thanks to several factors. For one, shock absorbing materials in the sole attenuate the initial impact transient by approximately 10% and increase the time over which the impact transient occurs, making RFS more comfortable than if it were done barefoot [18]. Additionally, by design, conventional running shoes typically feature a tapered midsole that is higher and thicker at the rear of the foot. This wedge shape encourages the heel to make contact with the ground before the forefoot does.

Lieberman et al. also provide mathematical calculations based on the momentum of a runner's body to determine the effective mass producing the impact transient. From simple physics,

$$F = \frac{dp}{dt} \tag{1.3.1}$$

where F is force and $\frac{dp}{dt}$ is the rate of change in momentum. Lieberman provides a modified version of Equation 1.3.1 to calculate the effective mass:

$$\int_{0^-}^{T} F_z(t) = M_{body}(\Delta v_{com} + gT) = M_{eff}(-v_{foot} + gT) \tag{1.3.2}$$

Here, $F_z(t)$ is the time-varying ground reaction force, 0^- is the moment in time before the impact transient begins, T is the duration of the impact transient, M_{body} is the mass of the body, v_{com} is the vertical velocity of the center of mass, g is the gravitational constant, v_{foot} is the vertical velocity of the foot just before impact, and M_{eff} is the effective mass [18]. For FFS, where the impact transient is not present, T is determined by $6.2 \pm 3.7\%$ of stance [18]. To solve for M_{eff}, variables are moved around to produce

$$M_{eff} = \frac{\int_{0^-}^{T} F_z(t)dt}{-v_{foot} + gT} \tag{1.3.3}$$

Using experimental data, Lieberman et al. were able to determine that the average M_{eff}, normalized to M_{body}, was $6.8 \pm 3.0\%$ for barefoot RFS runners and $1.7 \pm 0.4\%$ for barefoot FFS runners [18]. In conclusion, it appears FFS runners have a collision force with the ground that consists of a much lower effective mass than RFS runners.

This data seems to make a case clear, that front-foot striking is much better for the body than rear-foot striking. One may be led to believe that since modern running shoes encourage RFS behavior, the best way to run must be to do it barefoot! Minimalist running shoe companies and barefoot running enthusiasts have taken advantage of the RFS vs. FFS debate to promote the benefits of their own products and techniques and decry the "plague" that is the standard, foam-heavy running shoe. However, as Lieberman et al. note themselves, fore-foot running in one's naked feet is not without its own disadvantages. First and foremost, people already accustomed to a lifetime of running RFS in regular running shoes will most likely find it difficult or cumbersome to train themselves to run FFS [18]. FFS requires stronger feet and calf muscles, and novice runners are prone to developing Achilles tendonitis [18]. In addition, running with foam and rubber-soled shoes has the much-needed benefit of protecting one's feet from urban and man-made debris such as glass, nails, and other

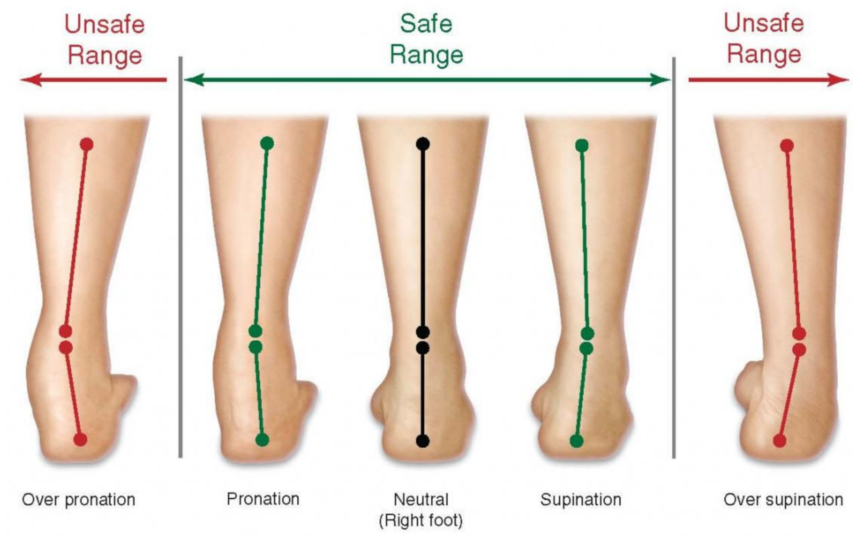

Figure 1.8: Diagram of pronation to supination spectrum as viewed from the posterior of the foot [19]

sharp objects that are not normally found in nature, and that barefoot humans in prehistory most likely would not have encountered on a normal basis.

Runners with certain anatomical characteristics also benefit more from running with conventional running shoes. These include people whose feet display overpronation or oversupination, dramatic ankle rolling in the medial and lateral directions, respectively. Most running shoes are designed with stability in mind, and many feature innovations with pronation and supination in mind. For example, wedged insoles and midsoles that are thicker towards the medial side of the foot help overpronated feet by forcing the foot to roll outwards [2]. Midsoles with variable density can also help. Denser foam will compress less than lighter foam such that when the foot strikes the ground, the foot will begin rotating towards the direction of the more compressible foam. Therefore, creating a design that positions the more compressible foam opposite of the direction the foot has a tendency to pronate/supinate will also assist in keeping the ankle in a straight position [2].

Despite evidence that suggests barefoot running and front-foot striking are gentler on our bodies, running shoes most certainly still have a place amongst our wardrobes. They do what our bare feet can't, keeping the dangerous and unpredictable world at bay and preventing other types of injuries that barefoot running could in fact produce.

1.4 Motivation for Creating a Wooden Running Shoe

As shown thus far, footwear made for running and footwear made from wood have been around for millennia. However, the intersection between these two areas has, to the author's best knowledge, been nearly nonexistent. Especially in today's industry of highly-advanced materials and manufacturing processes, this intersection is easily overlooked.

However, there is still merit in taking the time to put the foams, plastics, and rubbers aside and scrutinize what wood could mean for running. The author's basis for pursuing the creation of a wooden running shoe is threefold:

1. **To bridge the unbridgeable:** Can the common notion that wood is a solid, unyielding material be shattered? Can wood be made to absorb shock like a traditional midsole?

2. **To explore the aesthetic value of wood:** Can the unique beauty of wood shine on a pair of shoes as it does in furniture and architecture? Will wooden running shoes have the right aesthetics to attract potential wearers?

3. **To paint a greener picture:** Could a running shoe made of wood and other renewable/environmentally-friendly materials perform as well as, if not better than, a standard running shoe made of synthetics? Are there organic materials that possess similar properties to foams and other elastomers?

On the 1st point, wood is one of nature's great engineering materials. Its hardness, rigidity, and relatively low density compared to other materials like stone and metal have made it the choice material for all types of items where those properties are needed, such as buildings, cartwheels, tool and weapon handles, furniture, and of course, clogs. While wood is great for these applications, these very properties are why wood may be perceived to be the *last* choice of material for a running shoe that requires flexibility and cushion. That being said, there are cases throughout history of wood being used as a flexing mechanism that bring solace to its feasibility in running shoes. The most prominent examples are bows and — of a more modern era — longboards. Bows deflect a significant amount to store potential energy to launch an arrow hundreds of feet. Historically, bows have been crafted from both solid and laminated pieces of wood, techniques differing by time and location [20].

Figure 1.9: Longboard flexing under body weight [21]

They must undergo incredible amounts of stress without breaking to send arrow after arrow. Longboards also must be able to bear the load of a human body and more. By laminating thin sheets of wood called veneer with certain types of glue, longboards fractions of an inch thick can be made with extreme flexibility to absorb shock from bumps and other features of unsmooth terrain. Figure 1.9 shows just how much deflection a longboard can sustain without breaking. Bows and longboards serve as inspiration for how laminated wood may be able to flex to attenuate shock and support a person's weight without breaking in footwear.

On the 2nd point, wood has been prized just as much for its appearance as its mechanical properties. When stained, oiled, or even left in its natural state, different species of wood will display very unique patterns and grains that are highly sought after. High end furniture made from rare, beautiful woods can sell for tens of thousands, if not more. Many examples of modern architecture also feature unpainted wood as a key aesthetic element. The author's own travels to East Asian countries like China and Japan have brought him to the sites of magnificent temples and historical buildings made almost entirely of wood. This beauty may be captured in an unprecedented way when crafted into a shoe. Instead of a bland chunk of foam for a midsole, the grains from a piece or pieces of wood may lend a dazzling complexity to the appearance of the sole and draw eyes to the wearer's feet. In today's fashion-forward society, consumers make the decision to purchase athletic shoes based off of both performance and aesthetic factors. How a wooden running shoe will look is an important aspect to keep in mind as it will determine its social value.

On the 3rd point, wood, unlike petrochemical-based plastics, is a renewable resource. In addition, it is easily biodegradable and does not necessitate the type of complex processing that petroleum does to become something that can be used in a shoe. A responsible and ethical engineer needs to keep the environmental impact of a project in mind. A good design is one that not only works, but also minimizes the disturbance it causes to the world's resources and to the environment around it. If a running shoe made from wood and other sustainable, organic resources like plant-based fibers can match the performance of one made from synthetics, there could be implications about increasing the sustainability of the footwear industry. A major challenge would be finding organic materials that possess the same characteristics as the engineered plastics used in current running shoes, or finding a way to process natural materials to have those characteristics.

Chapter 2

Initial Design Concept

2.1 Related Existing Designs

Several existing running shoe and running apparatus designs were analyzed as potential starting points for a wooden spring-actuated shoe. They were the Adidas Springblade, Mizuno Wave, and Flex-Foot Cheetah. What makes these three products stand out is that they feature systems of shock absorption that stem from mechanical deflection rather than the standard foam compression found in conventional running shoes.

Adidas Springblade

Figure 2.1: Adidas Springblade [22]

The Adidas Springblade features a row of thin cantilever springs that project diagonally down and backwards from the sole. These cantilever springs, or blades, work simply by deflecting upwards towards the foot under load and store energy until the load is taken off and the blades return to their original position. Adidas has released several different models of its Springblade shoes, with the newer versions featuring shorter blades near the front of the shoe.

The blades themselves are made from plastic and are directly extruded from the base plate, which appears to be made of the same material. While this is an easy method of manufacturing for plastics, finding a way to attach wooden blades at such a steep angle to the rest of the shoe — and so many of them at that — is a significant challenge. Gluing wooden blades might be too fragile unless the adhesive interface of each blade had a high surface area. This would be a problem of available area as blades would be competing for room to glue. Bolting or screwing in that many blades would be an issue of weight and comfort. That many metal bolts or screws would increase the mass of the shoe significantly. Protruding bits would also present an uncomfortable scenario for the bottom of the foot, and may also interfere with blade actuation.

Mizuno Wave

Figure 2.2: Mizuno Wave Creation 13 [23]

The Mizuno Wave refers to a broad range of mechanical plate technologies featured in various Mizuno running shoes. Thin, plastic plate-like inserts that run within a foam midsole feature wavy patterns that deform and flex to help absorb impact, as the company claims [24]. In its most dramatic incarnation, the Mizuno Wave starts as a modestly inconspicuous piece in the forefoot sandwiched by foam and becomes a standalone system under the midfoot and heel, as seen in Figure 2.2. While the shock absorption is also achieved through deflection of a mechanical structure in the Mizuno Wave, the structure is more akin to a multi-support horizontal beam than the near-vertical cantilever beams in the Adidas Springblade.

Unlike the many blades in the Adidas Springblade, the Mizuno Wave could potentially be made from a single piece of laminated wood, curved and molded to provide the right shape. The Mizuno Wave also inherently has more surface area to work with given its parallel orientation to the sole of the shoe, and thus adhesives may be feasible. The "supports" could be small, block-shaped inserts made of wood or cork. A challenge would be finding the right substitute for the volume of foam in the forefoot. The wave structure in the rear of the foot could instead be continued through to the front of the shoe. Substituting solid wood for the foam may be both uncomfortable and heavy.

Flex-Foot Cheetah

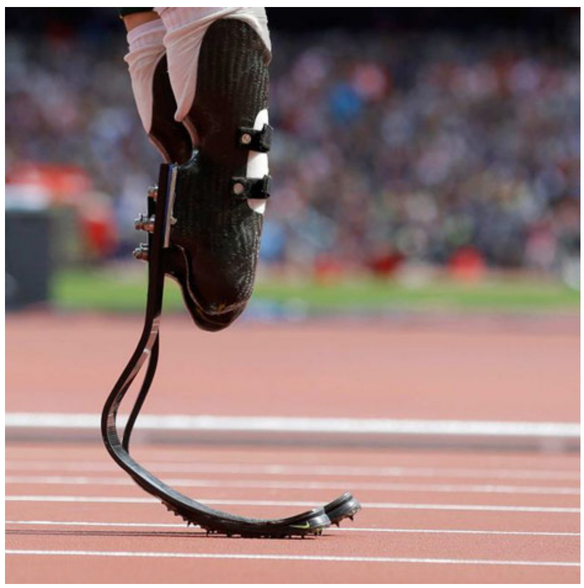

Figure 2.3: Flex-Foot Cheetah [25]

The Flex-Foot Cheetah by Icelandic orthopedics company Össur is a prosthetic running attachment that replaces the lower leg and foot of amputee runners. The single-bladed design is created from layers of carbon fiber. Depending on the situation, the Flex-Foot Cheetah features a modular system of soles that can be swapped out, providing various possible grips. The Flex-Foot Cheetah's method of actuation is a hybrid of the Mizuno Wave and Adidas Springblade. It acts more like a buckling column under load, but also has a cantilevering component where the foot begins to curve to a horizontal.

Despite being designed for Paralympic athletes, the Flex-Foot Cheetah could be scaled down and used directly under the foot in a shoe. The thinness that can be achieved by the Flex-Foot Cheetah is facilitated by carbon fiber's properties. For the same dimensions, wood will be weaker. However, the singular design is simple to manufacture and can be easily produced by laminating wood.

2.2 Sole

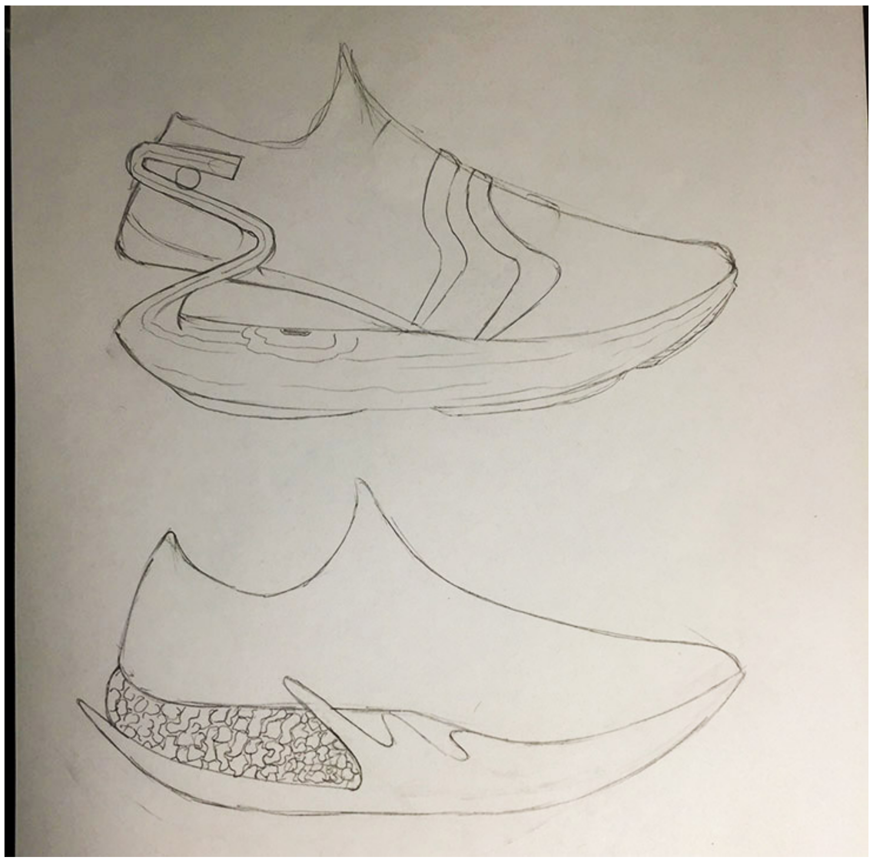

Figure 2.4: Early concept drawings

Early design concepts for the shoe focused primarily on the sole, as having a good working mechanism for shock absorption was cardinal to the comfort performance of the shoe. Figure 2.4 depicts two rough concepts for the sole mechanism. The top drawing features a complicated, Z-shaped spring at the heel that compresses downwards when a load is applied. The heel of the foot hovers above the wooden sole and is able to float downwards when the spring compresses. The idea was to have the spring and wooden sole made from a single piece of wood or laminated, glued, and cut out precisely for a seamless design. The sole is enlarged in the drawing and would be made much thinner in reality. In addition, the entirety of the sole from front to back would not have to be made of a single piece of wood as shown. Variations with grooves cut out to create even thinner sections in the sole that could allow it to bend and have flexibility were also considered as a possibility.

This design was cause for major concern despite its incredibly unique look. For one, the complexity and number of bends of the Z-shaped spring could prove to be a manufacturing nightmare. If it were too delicate and poorly-made, it would easily snap into several pieces, especially under the 1.5-3 times body weight load predicted to be enacted on the shoe (see Section 1.3). The height of the floating heel might also cause discomfort as the foot would be biased forward inside the shoe. Debris could also make its way into the gap while running and become trapped. This would cause an unexpected jolt of pain if the wearer's heel was able to come down and make contact with the foreign matter. How the upper could be joined robustly to the spring was also a point of curiosity. The spring would also have to be attached on either side of the upper since a foot and ankle would be located in that location within the upper. This could cause issues with the spring, if it protruded laterally far enough, chafing against the opposite foot or leg.

Due to these issues, a second concept (at the bottom of Figure 2.4) was conceived with a much simpler design. A cantilevered wood laminate spring would run from the front to the back of the shoe at the bottom of the sole. The front would be its anchoring point, directly attached to the upper. At the rear, however, the spring would be separated from the heel of the foot by some matrix of softer wood or hollowed, woody tubes (the area drawn with a bubble-filled pattern). As the heel makes contact with the ground, the cantilever spring would deflect upwards into the matrix of material, compressing it to absorb energy. The spikes protruding from the wooden spring around the midfoot in Figure 2.4 were solely drawn for aesthetic purposes in an attempt to break up the straight lines of the spring.

Despite the simplicity of this secondary design, there were still some red flags that popped up. The matrix under the heel would be difficult to tune to have the right compressive strength. Even if a soft wood were used, it would still be a solid block without much compressive give. A matrix of hollowed, woody tubes may be *too* forgiving and, like a literal bunch of sticks, simply crack and break apart. An additional variation of this concept was to forgo the matrix altogether, allowing the cantilever spring to act as the sole mechanism of shock absorption and once again a floating heel design. However, that would require the bottom of the upper to be rigid enough to support a heel suspended in the air. Otherwise, it would feel akin to having one's heel held in a bag above the ground.

After taking all these points into consideration, a design was created ready for the 1st iteration of modeling, manufacturing, and testing. A sketch of the sole of this design can be seen in the top left of Figure 2.5. This sole features a single piece of laminated wood that begins at the heel, curves under at the toe, and continues back to the heel to create a cantilever "springboard" design. This double-decker allows the foot to be supported by the laminate with a floating design. The front half of the gap made in the laminate is filled once again with a matrix of organic material with some amount of compressibility. However, in this design, it is not as crucial because it is located in the forefoot where shock attenuation is less important. The heel, as stated, is floating and the cantilever becomes the sole mechanism of shock absorption. The singular design, like the Flex-Foot Cheetah, is conducive towards ease of manufacturability and the amount of material usage. Laminated as opposed to solid wood was chosen because of lamination's ability to minimize the effect of natural defects present inside wood, such as cracks and weak grain lines. By cross-laminating in alternating grain directions, the anistropic nature of wood can be made more isotropic. Lamination with thin pieces of veneer also allows the generation of more drastic curves, as each thin piece is able to bend much more than one thick chunk of wood.

2.3 Upper

In initial designs, the upper was made of traditional, fabric-based components sewn together and laced to tighten around the foot. Due to the existence of the metatarsal bones at the top of the foot and the generally more delicate nature of the top of the foot relative to the sole, wood was not considered as a major material for the upper. The upper requires flexibility and the ability to form around the contours of the foot. Wooden components, unless very thin and prone to snapping, do not have the same degree of conformability as textiles do. Wood's hardness would also present issues with the metatarsal bones, creating uncomfortable pressure.

A few straps made of wood in certain areas of the upper were considered. However this was quickly determined to be redundant to a lacing system and a method of holding the straps in place would be difficult to create. Instead, a series of loops of thread or thin twine were decided upon for the laces to loop through. These loops would run along the sides of the upper as shown in the drawing dead center in Figure 2.4. When the shoelaces are tightened, the loops become taut and lock down on the foot beneath. Unlike a traditional lacing system with eyelets punched into the upper, the thread is able to put pressure in discrete locations along the foot, whereas a single piece of fabric tightened through eyelets would apply uniform pressure over a larger area and be unable to hug complex curves.

Textiles can come from natural sources such as cotton, hemp, and linen. This was considered during the initial design process and supported the use of a fabric upper.

2.4 Heel Counter

The final component considered during the initial design phase was the heel counter. To compensate for the flatness of the laminated wood sole, which would provide little to no lateral reinforcement, an oversized external heel counter was designed that would extend further towards the midfoot than conventional counters in running shoes do. The walls of the heel counter would help prevent the foot from rotating side-to-side and to prevent lateral slippage as well. In addition, the heel counter would act as a skeleton for the upper, which due to its all-fabric construction, would not be able to hold its own shape and stay upright.

The heel counter was designed to also be made of laminated wood, though much fewer layers would be used than for the cantilever spring in the sole because the heel counter would not need to undergo the same magnitudes of force. Because the heel counter is made of wood, it would wrap around the outside of the upper as opposed to the inside, where the hardness of the wood could cause discomfort around the bony heel.

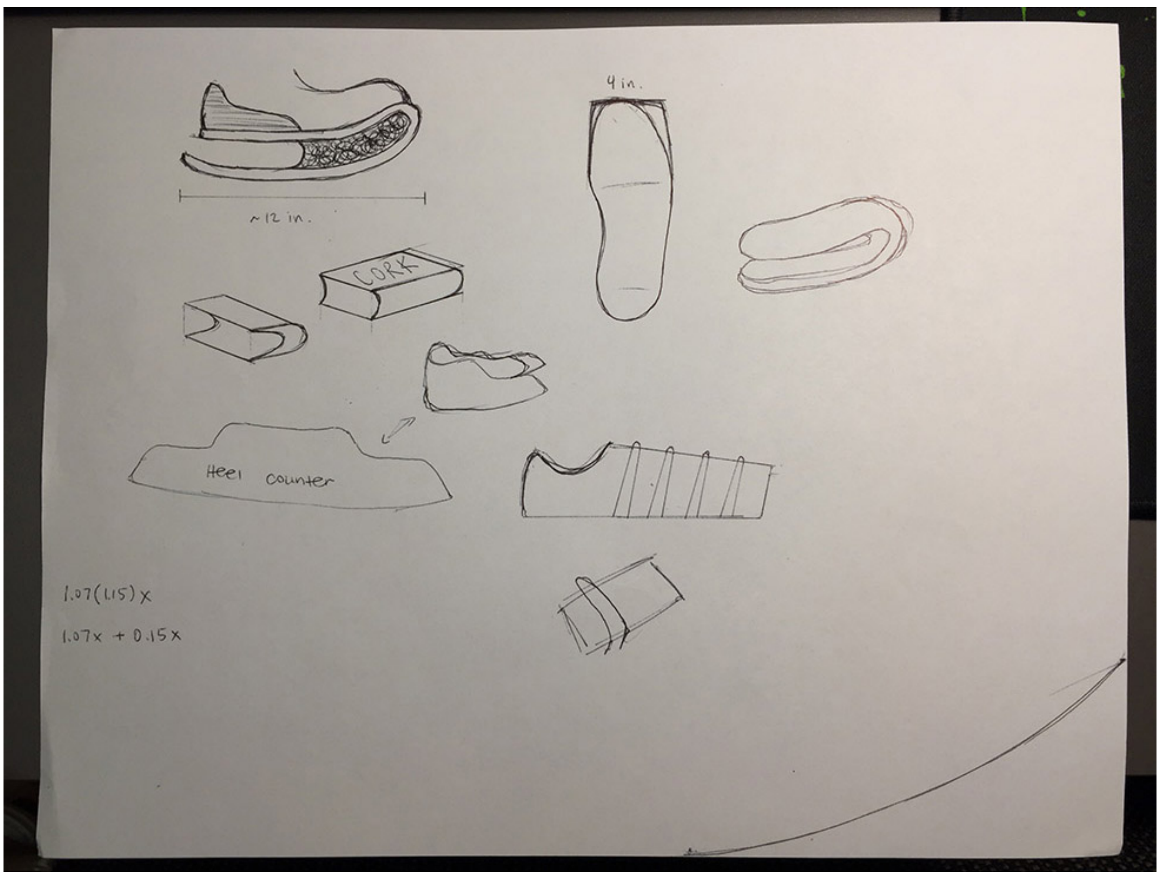

Figure 2.5: Rough sketches for the 1st iteration of design

Figure 2.6: Digital drawing of the proposed design

Chapter 3

Materials Selection

With the initial design ready, the next step was to determine which specific materials would be used for each component of the shoe. Wood would be used for the sole, but many species exist and properties can change dramatically between them. The type of natural fiber to be used for the upper also needed to be determined. Lastly, the method of joining everything together, be it mechanically or with adhesives, needed to be determined.

3.1 Sole Material

Wood Spring Material

Determining what type of wood would be used to create the laminated sole came down to three variables: modulus of elasticity (MOE), modulus of rupture (MOR), and density. The MOE is a measure of how flexible the wood is. Therefore, for the purposes of the shoe, a lower MOE was desired to allow for the cantilever spring to flex. The MOR is a measure of the strength of the wood. The higher the MOR, the more force it takes to break the wood. Naturally, the highest possible MOR is desired such that the cantilever spring will not break. The density of the wood is also important as it will determine the weight of the shoe. If the wood has too high a density, the shoe will feel heavy and cumbersome. As such, a low density is desired so that the shoe feels weightless against the foot.

Values for different woods were pulled from the *Wood Handbook* published by the USDA and Forest Service and other scholarly publications [26][27]. Exotic and rare woods were not considered because of cost, difficulty of obtainment, and lack of sustainability. From the list of woods, four finalists were evaluated as having the best balance of the three properties. Table 3.1 lists the four types of wood as well as their respective properties (density is listed in terms of specific gravity).

Table 3.1: Properties of Select Woods

Wood	**MOE (GPa)**	**MOR (MPa)**	**Specific Gravity**
Moso Bamboo	9	90	0.6
Rock Maple	12.6	109	0.63
Birch	13.9	114	0.62
White Ash	12	103	0.6

Ultimately, the best "wood" found for the job was *Phyllostachys pubescens*, more commonly known as Moso bamboo. Though technically considered a grass, Moso bamboo possessed the best group of properties among the four woods. It has the lowest MOE, making it the most flexible material on the list. Although its MOR is also the lowest, it is only fair to consider the strength-to-flexibility (MOR/MOE) ratio. In this case, Moso bamboo has the highest ratio among the four. Moso bamboo also has the least density with a specific gravity of 0.6, only equaled by White Ash.

Moso bamboo can grow up to 119 cm in 4 hours and reach lengths of 25 meters [26]. This makes it a highly suitable candidate from a sustainability perspective. Moso bamboo can be grown and harvested at a much quicker renewal rate than the other woods on the list, whose full-grown trees can take years to develop.

Figure 3.1: Striped pattern visible on a sample of bamboo [26]

Aesthetically, bamboo has its own unique pattern. Due to the many vascular bundles that run length-wise within the bamboo, a striking striped pattern tends to be visible on most samples, such as in Figure 3.1. This could lead to a very eye-catching sole for the shoe.

Logistically speaking, Moso bamboo veneer was also easier to find than that of the other woods, especially in the very small thickness needed to laminate the sole and its extreme front curve.

Matrix Filler Material

The matrix filler material was responsible for providing support to the cantilever spring during loading and for restricting some torsion in the sole of the shoe. Soft, solid wood was considered but quickly ruled out due to the weight disadvantages of having a solid chunk of wood in the front of the sole. This would make the shoe front-heavy and feel unbalanced on the foot. Additionally, soft wood would simply undergo plastic deformation since wood does not have good elasticity in compression.

A clear choice for the matrix material was cork. Cork is the naturally waterproof, air-filled bark of the cork oak. The closed-cell structure of cork essentially makes it a foam, and thus enjoy properties such as compressibility and light weight.

Cork, a common material in construction and even certain types of footwear, is easy to find and comes from a non-destructive, renewable source (the cork tree is not killed to harvest its bark).

3.2 Upper Material

Figure 3.2: Hemp stalk with fibers visibly peeled [28]

Natural fibers considered for the upper included cotton, linen, and hemp. The textile needs to be strong to resist the wear and tear of ground-level debris and dirt. It also needs breathable and comfortable to the touch. In terms of these specifications, all three of cotton, linen, and hemp pass as adequate materials. However, hemp's historical durability and ease of growth made it the winner.

Hemp was a major crop throughout history to many different civilizations. It has been favored for its strength and was therefore a traditional material for sails and ropes. In fact, hemp is 3 times stronger than cotton and resists saltwater [29]. Hemp's notorious other name, cannabis, is the basis for the word "canvas" [29].

Hemp also has fantastic environmental benefits. It grows well in many types of climates and soil types, thereby reducing the need for fertilizers and other growth stimulants [30]. It is naturally resistant to pests, reducing the need for toxic pesticides. It also grows well in condensed areas, freeing up more land for other uses [30].

All these benefits of hemp made it the author's pick for the upper material. Hemp is also unfairly confounded with marijuana in modern society, creating major barriers against it gaining a significant foothold despite its industrial usefulness, especially in the US. As such, the use of hemp in this thesis is partially to bring attention and advocacy to this well-deserving material.

3.3 Heel Counter Material

Moso bamboo was once again determined to be the best choice for the heel counter. Although the heel counter does not experience the same magnitude of force as the cantilever spring sole and therefore could have used a weaker (less MOR) but lighter wood, other factors came in play that ultimately made Moso the best choice regardless. For one, keeping with the same material as the sole minimizes material sourcing and saves costs. In addition, lighter woods sold at the thinness needed for the heel counter were very difficult to find. The minimal amount of material needed to make the heel counter also meant that the weight savings from using a lighter wood would be negligible.

3.4 Adhesives

Both mechanical and chemical methods of joining the parts of the shoe together were considered. However, mechanical joinery fell out of favor because of the weight that would be added and the potential for creating stress fractures and other defects at the point of connection.

The best option was to use a water-based contact cement to join the different components. A water-based contact cement does not contain harmful/polluting solvents and can be cleaned up easily. An advantage of using a contact cement is that bonds are instantaneous. The contact cement is applied to both sides of an interface. When the cement dries, the two items can be brought together, and with some pressure, will be bonded instantly without the need for vices or clamps to hold the connection in place. Contact cement, unlike mechanical joinery, holds two items together over the entire area on which it was spread, relieving hot spots of pressure. Contact cement is also very versatile, able to bond wood to cloth, precisely what the shoe needs.

A glue was also needed to laminate the Moso bamboo layers to create the heel counter and cantilever spring. Specialized water-based glues are available made specifically for creating flexible glue lines. Glues made just for skateboards and longboards even exist. These will work equally well to create a dynamic shoe sole that needs to undergo a lot of stress and flexing.

Chapter 4

1st Iteration

Having chosen and obtained all the necessary materials, the manufacture and assessment of the 1st iteration of the shoe was underway.

4.1 CAD Models

First, CAD models of the shoe's components were created using Creo Parametric 3.0 software. The hemp fabric upper was not modeled due to the complexity of surfacing needed to recreate a convincing model. In addition, the pliability of the upper meant it contributed negligibly to the structural integrity of the shoe and would not be necessary for finite element analysis through Creo Simulate later on.

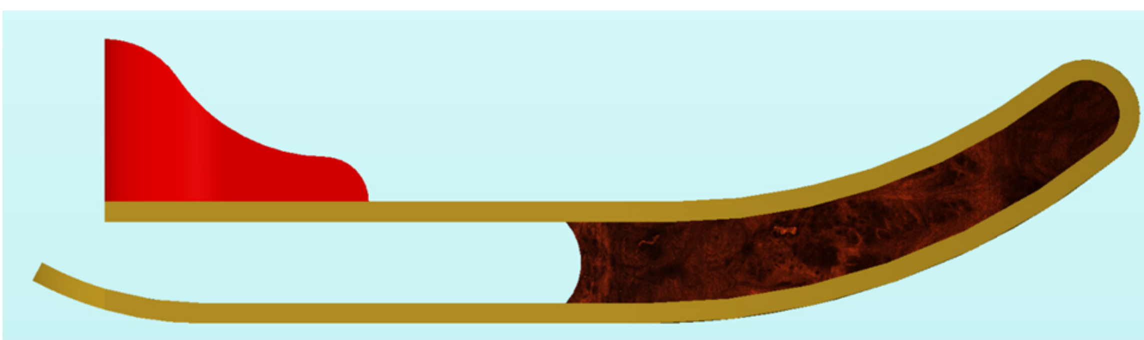

Figure 4.1: Shoe assembly without upper (side view)

In the assembly model as seen in Figures 4.1 and 4.2, the heel counter (red), bamboo cantilever spring (yellow), and cork fill (brown) are shown in their respective locations. The heel counter was modeled in both 3-D and a flattened 2-D quilt that would be used for creating stencils to trace onto sheets of bamboo veneer.

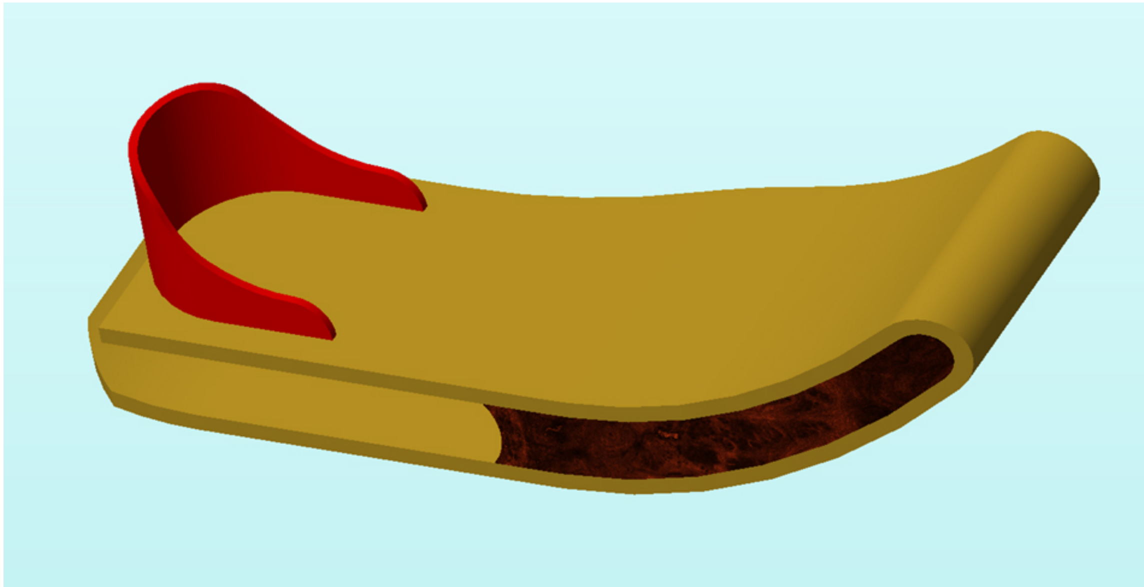

Figure 4.2: Shoe assembly without upper (isometric view)

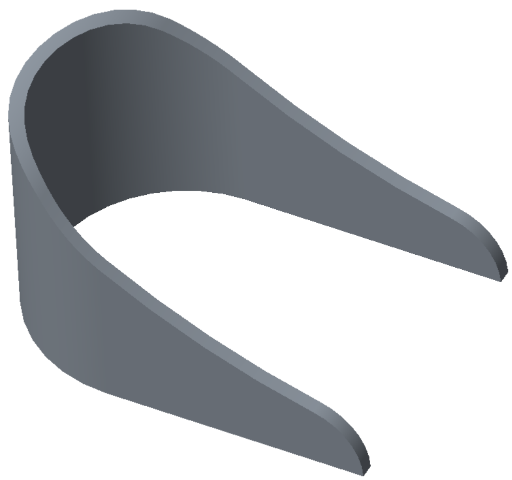

Figure 4.3: Heel counter (3-D)

Figure 4.4: Heel counter (2-D)

The length of the sole, from back to front, was determined by measuring a pair of the author's size 10 Mizuno running shoes. This value came out to be approximately 11.5 inches. The width of the shoe varies based on the contours of the feet, from 3 inches around the heel to 4 inches at the widest part of the foot. The height of the heel of the sole (measured from the ground to the top surface of the cantilever spring where the heel rests) is 1.6 inches. This is comprised of the thickness of the cantilever spring (0.3 in.) x2 plus a 1 inch gap. The height of the heel was also determined in part by measuring some of the author's existing shoes. Special attention was paid to finding the right size of the gap and cantilever spring thickness. If the gap was too large, the heel would be too far off the ground, turning the shoes into a pair of high heels. On the other hand, if the gap were too small, deflection in the spring would cause the two surfaces to hit each other. In addition, a limiting factor was the front of the shoe where the spring curves essentially 180°. Due to this extreme bend, the radius of curvature could not be so small that the bamboo would snap. An appropriate diameter of curvature of 1 inch was determined, which then dictated the 1 inch gap at the heel. The allowable radius of curvature was determined by hand-bending samples of bamboo veneer until they snapped and measuring the radius at that point, as shown in Figure 4.5:

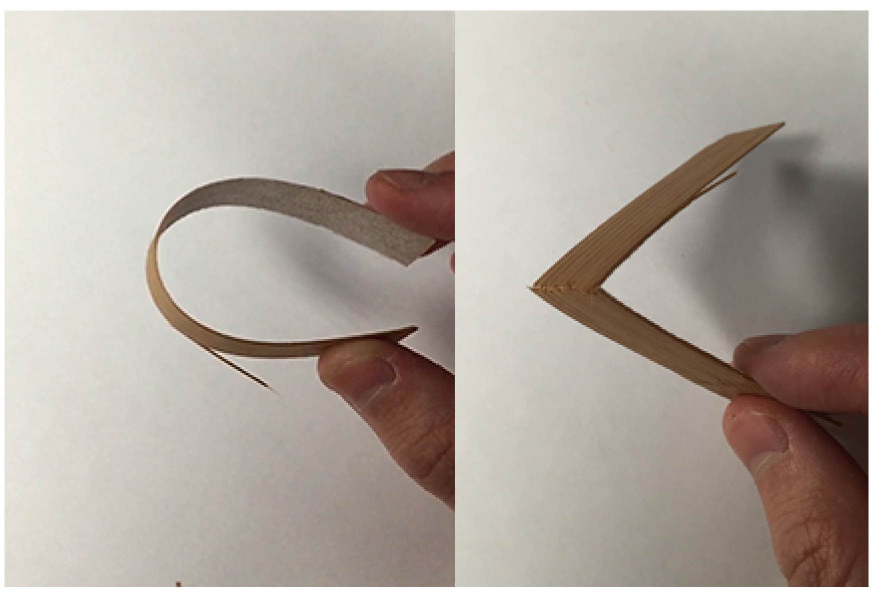

Figure 4.5: Measure the radius of curvature by hand

The height of the toe of the shoe (toe spring), which curves upwards, is 2 inches off the ground. This dramatic upwards sweep creates a rocker effect in the sole that compensates for the stiffness of the bamboo sole, allowing the foot to smoothly transition from landing at the heel to takeoff at the tip of the toes during running. These values are summarized in Table 4.1

Table 4.1: Critical Sole Dimensions

Dimension	**Value (in.)**
Length	11.5
Width	3-4
Toe Spring	2
Spring Thickness	0.3
Heel Height	1.6

The dimensions of the heel counter were modeled around the size of the author's heel. A height of 2 inches and a sidewall length of approximately 3 inches were determined to best hold the heel without cutting into the Achilles tendon when the foot was plantarflexed and while reaching the sides of the midfoot to effectively constrain the entire heel side-to-side.

A sole mold was also modeled. Its intended purpose, as the name suggests, was to allow the layers of veneer something to form over during the laminating process to create the shape of the sole. This file would be sent to the CNC to create a very precise, reusable mold.

Figure 4.6: Sole mold for laminating veneer

4.2 Manufacturing Process

Moso bamboo veneer was obtained from Northwest Bamboo in Corbett, Oregon. The veneer came in 4' x 8' sheets. Two thicknesses were ordered: 0.6 and 0.9 mm. The 0.6

Figure 4.7: Moso bamboo veneer

mm thick veneer was backed with a thin, paper fleece material to prevent the delicate veneer from splitting. This paper backing was considered to contribute negligibly to the structure of the sole due to its evanescent nature. The 0.6 mm thick veneer was favored and used initially due to its increased flexibility, which would help with creating the bend in the spring. The thinner veneer also allowed the total thickness of the sole to be more precisely built to the target 0.3 inches. Strips sized 4.5' x 26' were cut from the large sheets of veneer by hand using a large ruler, heavy-duty scissors, and a sharp X-Acto blade.

Figure 4.8: Veneer being cut to size

The sole mold was automated in a Bridgeport Torq-Cut CNC mill from blue

DOW Styrofoam-brand extruded polystyrene (XPS). This material was perfect because of its high compressive strength, low cost, ease to machine, and abundance in the Princeton University MAE machine shop. A couple of layers of XPS had to be glued together with Gorilla Glue to create a work volume with the right height that could accommodate the toe spring.

Figure 4.9: Sole mold at various stages of production

A steam bender was created from plywood to provide a way to temporarily soften the bamboo veneer to make it easier to create the bend in the spring. Through heat and steam, steam benders relax the lignin and wood fibers (or in this case, bamboo fibers), making the work piece more compliant to forming around curves. Steam was provided through a basic electric kettle piped into the main chamber by a short PVC pipe.

The adhesive used for the lamination process was Titebond III Ultimate Wood Glue, a popular choice for DIY longboard and skateboard builders [31]. Unlike resins and epoxies, this polyvinyl acetate (PVA) water-based glue is both non-toxic (in keeping with the environmentally-friendly mission of this thesis) and flexible when

Figure 4.10: Steam bender

dry, a crucial characteristic for a component that will be undergoing a lot of dynamic load. A foam roller was used to apply the glue evenly to each sheet of veneer (see Figure 4.11).

To create even pressure on the laminated veneer around the sole mold, a vacuum press was purchased from the Roarockit Skateboard Company (Figure 4.12). The vacuum press is comprised of heavy-duty vinyl that conforms and tightens around the object inside as air is evacuated via a small hand pump.

To reach the target thickness of 0.3 inches, 13 layers of 0.6 mm thick bamboo veneer were prepared with alternating grain directions (7 with the grain along the length of the strip and 6 with the grain running along the width of the strip). Laminating in this manner creates uniform strength in the finished piece because bamboo's anisotropic nature makes it much weaker in the direction perpendicular to the grain. The 13 layers were put inside the steam bender for 15 minutes to soften. After that, they were taken out and glued quickly all at once on a flat surface. 6 layers had been adhered together by the time the author noticed that the glue was becoming more viscous and starting to dry. The lamination process was prematurely brought to the next step, where the 6 layers were carefully wrapped around the sole mold like a taco shell by hand and held briefly in place by rubber bands. Finally, they were put inside the vacuum press and and left to cure overnight (Figure 4.14). The final remaining 7 layers would be glued and added to the existing 6 the next day.

Figure 4.11: Titebond III wood glue and foam glue roller

When the sole was removed from the press the next day, significant defects had formed. Large air pockets were visible at the top of the cantilever spring where the veneer layers wrinkled up against each other (Figure 4.15). The other components of the shoe were put on hold for the time being to investigate how this fatal error occurred and if the design of the shoe could be improved to fix it.

Figure 4.12: Roarockit thin air press (TAP) vacuum mold kit

Figure 4.13: Cross-laminating grain direction

Figure 4.14: Bamboo veneer inside vacuum press

Figure 4.15: Wrinkle defects in the cantilever spring

4.3 Testing and Simulating

4.3.1 Part Testing

The defective, 6-layer cantilever spring did not go to waste and was cut into pieces to perform tests on the bamboo laminate's mechanical properties. A complete 13-layer laminate test sample of the 0.6 mm thick veneer was also created, as well as an 8-layer test sample of the 0.9 mm thick veneer (approximately the same thickness as 13 layers of 0.6 mm thick veneer).

The modulus of elasticity (MOE) and modulus of rupture (MOR, or flexural strength) of the bamboo veneer were determined by a series of 3-point bending tests in an Instron Materials Testing Machine. The density of the bamboo was also calculated.

The MOE of a sample can be determined through a 3-point bending test by means of the following formula:

$$\delta = \frac{Fl^3}{48EI} \tag{4.3.1}$$

where δ is the displacement at the center of the sample caused by the force F. E is the modulus of elasticity, I is the cross-sectional area moment of inertia, and l is the span between the two outer supports. By swapping the places of δ and E in

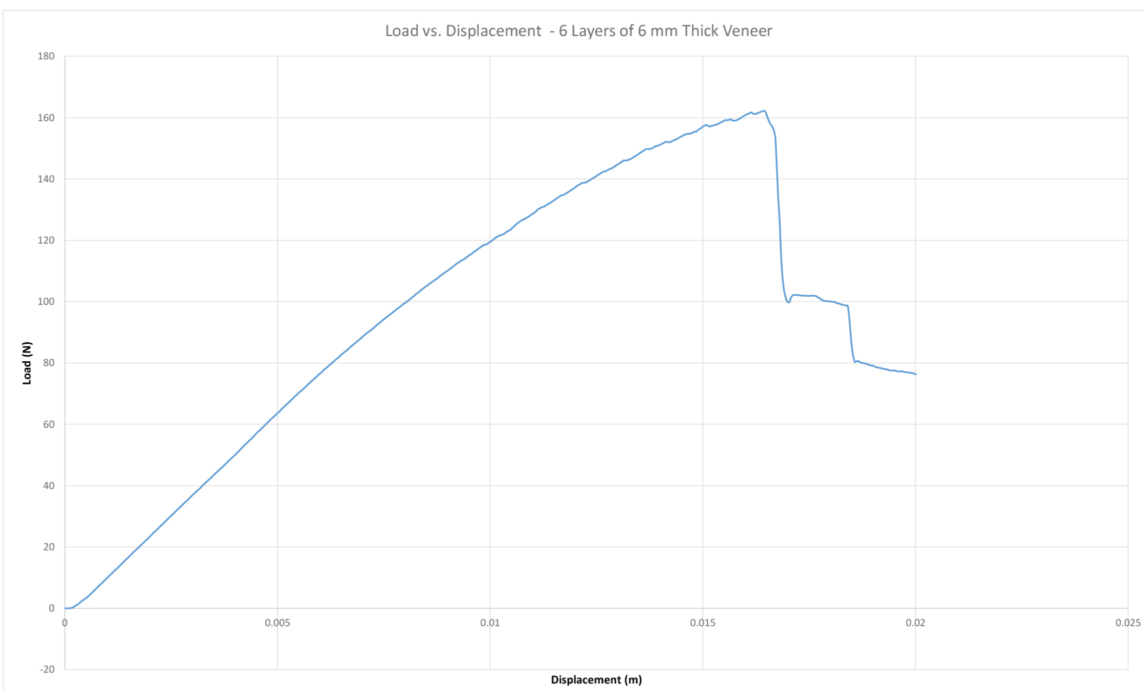

Figure 4.16: Load vs. displacement for 6 layers of 0.6 mm thick veneer

Equation 4.3.1, the MOE can be solved.

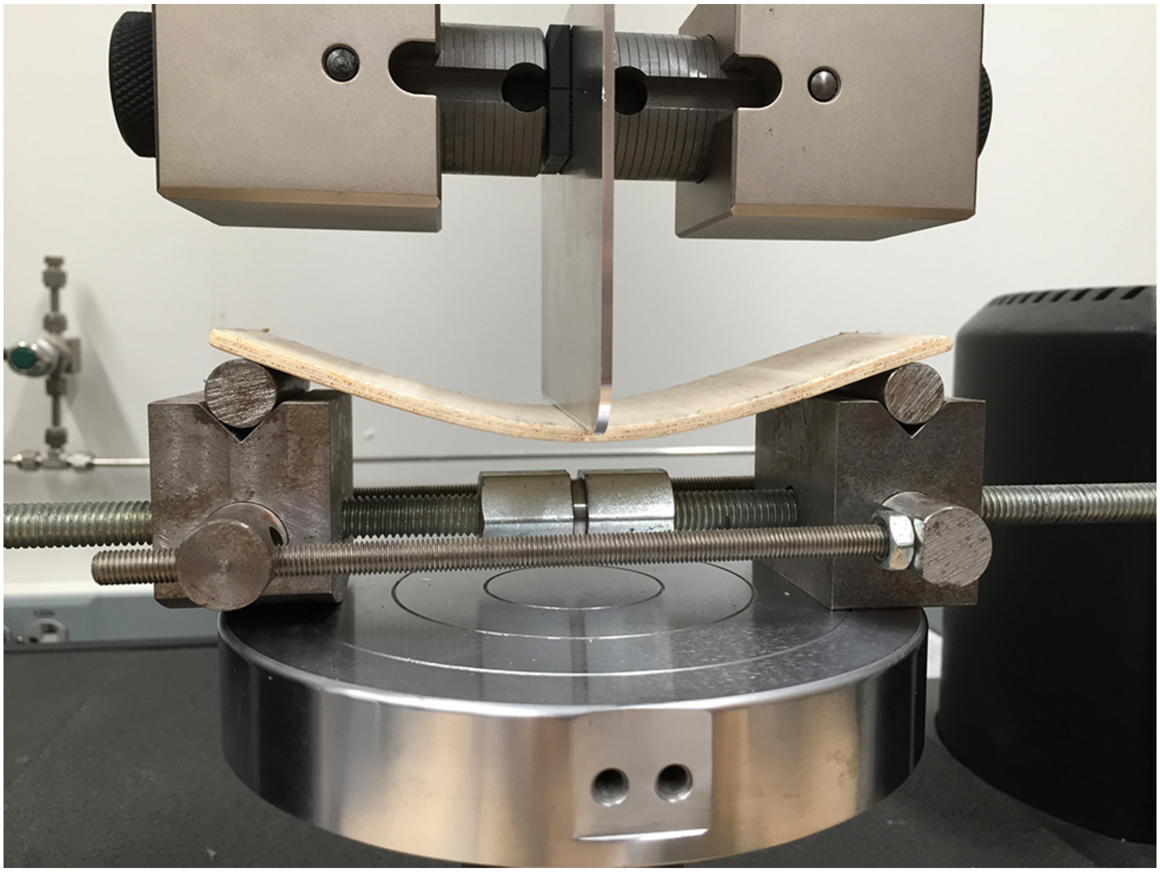

Figure 4.17: 3-point bending test

Figure 4.16 shows the load vs. displacement graph of the sample composed of 6 layers of 0.6 mm thick veneer. Using data from this graph and Equation 4.3.1, the MOE was determined to be **3.4 GPa**. In similar fashion, the MOE was **3.1 GPa** for the 13 layers of 0.6 mm thick veneer and **4.2 GPa** for the 8 layers of 0.9 mm thick veneer. These results show that the MOE for laminate made from 0.6 mm thick veneer is only approximately 1/3 of what was expected for Moso bamboo from Table 3.1. In addition, laminate made from 0.9 mm thick veneer appears to have a MOE that is roughly 30% greater than that of 0.6 mm thick veneer. This could be explained by the fact that in the same volume of material, a laminate made with 0.6 mm thick veneer has more glue than a laminate made with 0.9 mm thick veneer.

The modulus of rupture (MOR) can be determined by the following formula:

$$\sigma = \frac{3Fl}{2bd^2} \tag{4.3.2}$$

Here, σ is the modulus of rupture measured in units of pressure. F is now the maximum load before the sample breaks, whereas l is the same as before. b and d are the width and thickness of the test sample, respectively. The MOR was calculated as **52.5 MPa** for the 6 layers of 0.6 mm thick veneer, **42.5 MPa** for the 13 layers, and **51.1 MPa** for the 8 layers of 0.9 mm thick veneer. These values are almost half that of pure Moso bamboo. Cross lamination, albeit a good method of making a laminate uniformly strong, may be the culprit because technically only half of the layers are resisting load along the direction of the grain.

Density was found to be **725 kg/m³**. In terms of specific gravity, this is 0.725, compared to that of pure Moso bamboo, which is 0.6. The presence of PVA glue would explain the extra density in the laminate.

4.3.2 Finite Element Analysis in Creo Simulate

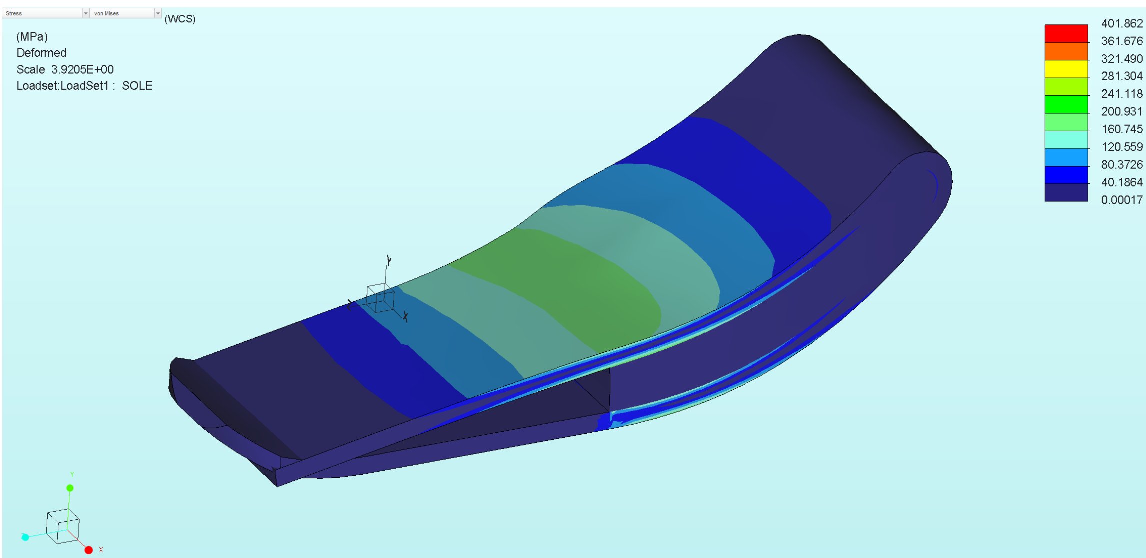

Figure 4.18: Simulation results for steel

The values for MOE and MOR were then taken in Creo Simulate to perform finite element analysis on the cantilever spring. For the sake of evaluating the integrity of the design, the spring was also modeled in structural ASTM-A36 steel with a MOE of 200 GPa and ultimate tensile strength of 400 MPa. A load of **1557 N** was applied across an area roughly the size of the author's heel to simulate the amount of force that is enacted during foot strike, which was chosen to be approximately 2.4 times the author's body weight (see Section 1.3 for more details). The bottom section of the spring was constrained.

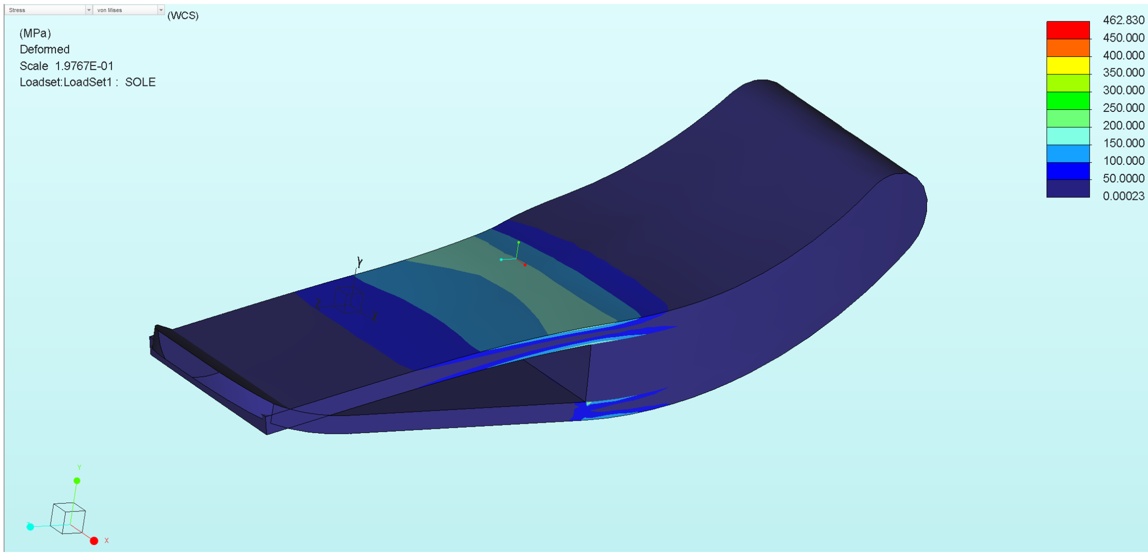

Figure 4.19: Simulation results for bamboo

Figure 4.18 shows that even with a sole made of steel, the force brings stresses in the spring close to half the ultimate tensile strength of steel, around 200 MPa. Made of bamboo, the sole experiences stresses close to 3 times the best-case MOR (52.5 MPa) determined in the previous subsection.

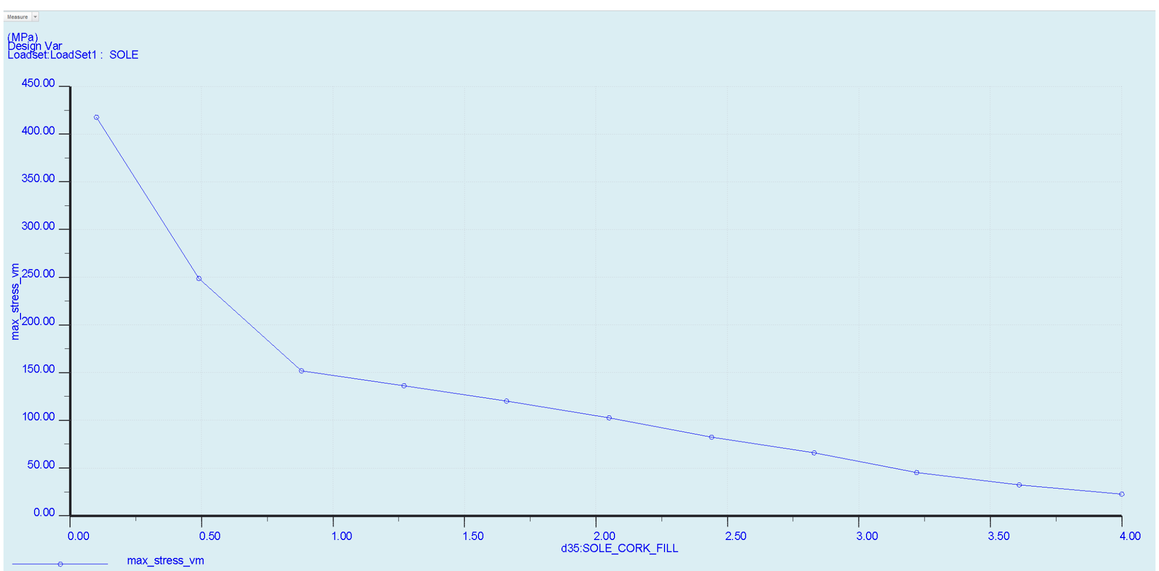

Figure 4.20: Cork length sensitivity graph, where the x-axis is the extension of the cork in inches towards the heel from its original location

A sensitivity study was created in an attempt to optimize the distance from the heel the cork is to bring stresses below the MOR (Figures 4.20 and 4.21). The study concluded that the cork would have to be extended 3.15 inches towards the heel for

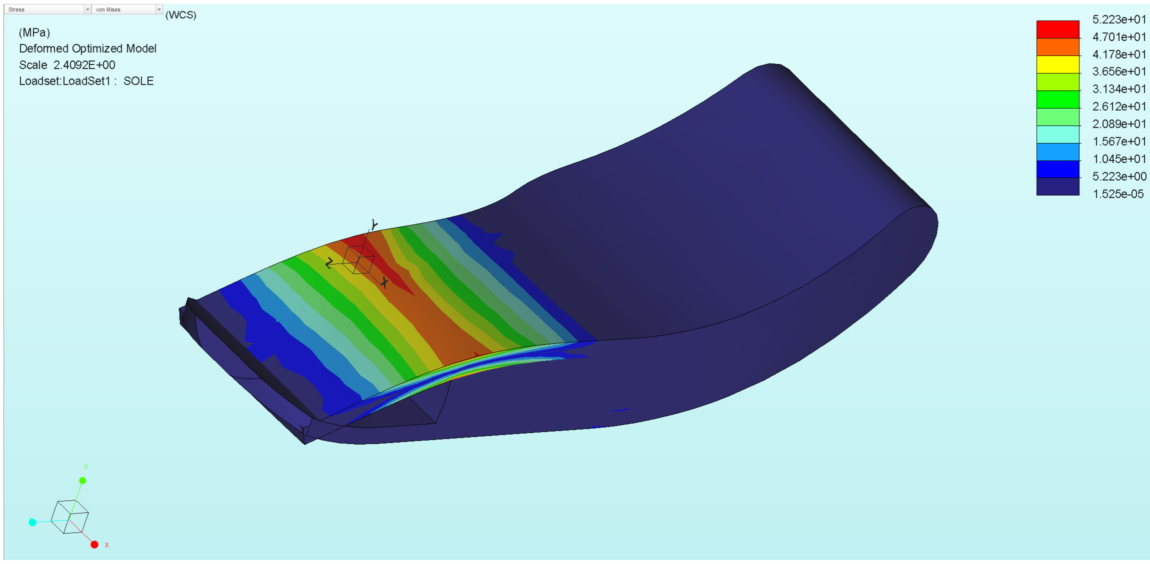

Figure 4.21: Bamboo sole with optimized cork length

the stresses in the spring to finally go below the value of the MOR.

4.4 Obstacles

The major obstacles with the 1st iteration of design had to do with the defects that threatened the integrity of the cantilever spring. A conscious choice was made to put production of the other components on hold and to figure out what went wrong in the spring and how it could be fixed. It was deduced that the air bubbles formed were the result of a two-pronged disadvantage in the design. The first thing was short working time of Titebond III wood glue relative to the number of layers that had to be glued. The ten minute window recommended by the manufacturer appeared to be more than adequate, but gluing and laminating thirteen layers ended up being a far more tedious task than the author had originally envisioned. By the 6th layer, the 10 minute limit was already reaching its mark and the glue was drying up. This increased the shear resistance between layers significantly and did not allow them to slide past each other as is needed to form around the mold.

The second issue was a matter of the dual concavity of the spring design. A change in concavity at the front of the spring, where the lamination needs to curve up and then bend downwards, was resisted by the bamboo veneer. Because of the 180° bend at the front, a lot of stress is located there, and trying to change concavity proved to be a bad idea. As such, due to these two factors, the material began to buckle and fold as the author tried to force it into shape.

After much consideration, the cantilever spring was overhauled in size and shape. It was moved strictly to the rear of the shoe underneath the heel, while the forefoot was replaced with a cork wedge. The cork wedge and new, smaller spring were bridged by a thin piece of laminate (as thin as the heel counter) that allowed far more flexibility than the original design, which needed a dramatic toe spring to compensate for the rigidity in the forefoot. This new design would be flexible enough to forgo the dramatic toe spring.

The changes made in the new design were drastic enough to push the shoe into its second iteration.

Chapter 5

2nd Iteration

5.1 CAD Models

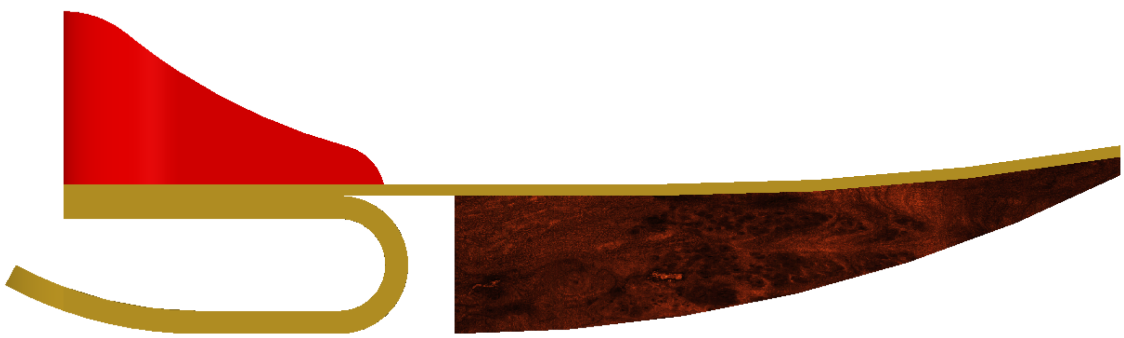

Figure 5.1: 2nd iteration shoe assembly, minus the upper

New CAD models for the different components were created. The upper's design did not change, and its process of manufacturing will be discussed in the next section. The cork was now a standalone piece that did not serve to support the cantilever spring, but rather held its own at the forefoot. The spring itself was moved only to where it truly mattered, under the heel, to attenuate shock from heel striking. As is noticeable, it has lost its dual concavity to ease manufacturing.

The cork has become the midsole alone in the front half of the shoe. It is no longer sandwiched between the cantilever spring. Because the cork is much more flexible than the laminated bamboo, a dramatic toe spring is no longer needed to facilitate the heel-to-toe liftoff, making the design sleeker and holding the foot in a more natural position.

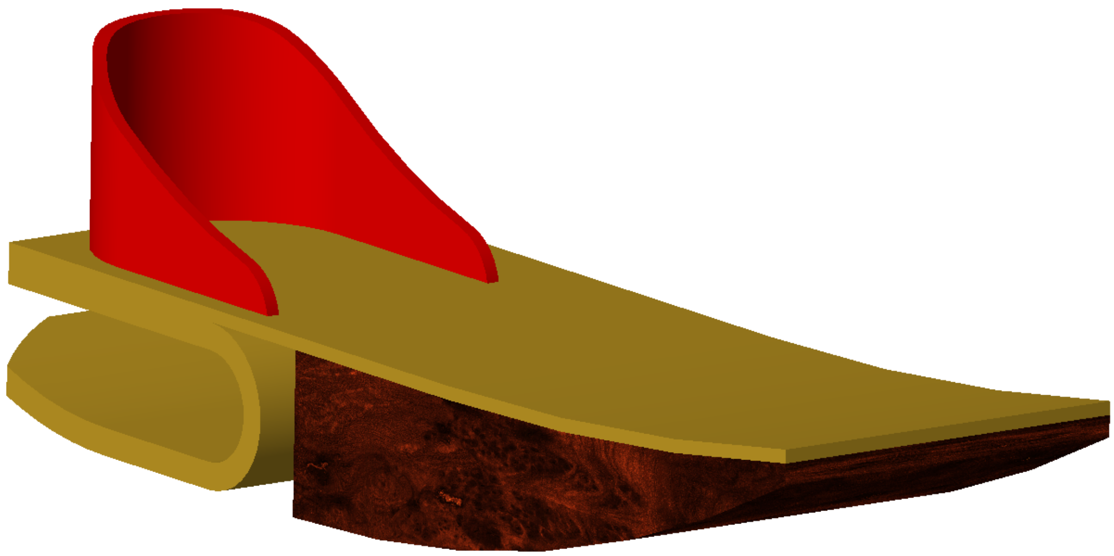

Figure 5.2: 2nd iteration shoe assembly, minus the upper

The thin layer of bamboo that bridges the heel and the forefoot is meant to be flexible and allow the shoe to conform more to terrain and the foot. Since it is under the plantar arch, it is a non-load-bearing member and thus can be made with 3 layers of 0.6 mm thick bamboo veneer just like the heel counter (which has not changed design).

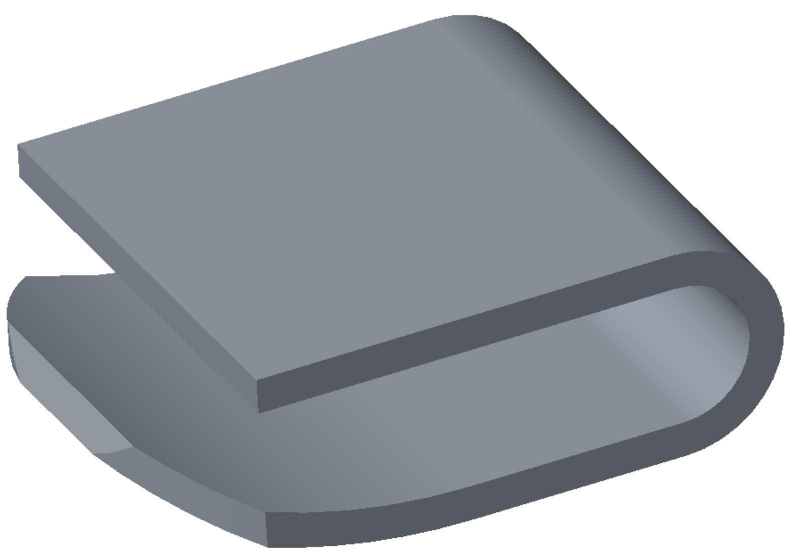

Figure 5.3: Cantilever spring under the heel

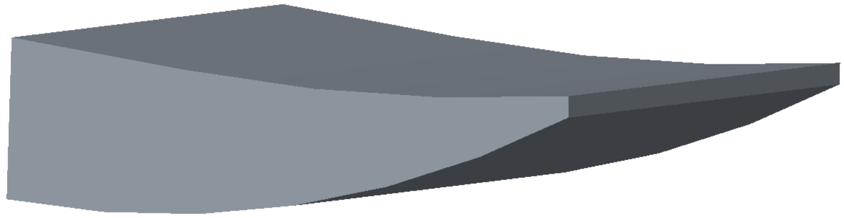

Figure 5.4: Cork midsole in the front half of the shoe

5.2 Manufacturing Process

Figure 5.5: New cantilever spring in vacuum press

The new cantilever spring was the first component to be manufactured once more. This time, care was given towards being cognizant of the working time of the glue. While much more time-intensive, the cantilever spring was laminated three layers at a time. Each batch of three layers was easier to manage and were more compliant. This method allowed the glue to stay wet and for the layers to slip by each other as they were curved around the new mold, which was also CNC'd from XPS. When the cantilever spring was finished, the thin bridge was then laminated (a one step process since the bridge was only made of three layers) and glued to the cantilever spring. The entire process was done using the vacuum press, an extremely versatile tool.

Layers of 6 mm cork, purchased in 24" x 36" sheets, were laminated using 3M

Fastbond water-based contact adhesive. A stencil made from the CAD model of the cork midsole was printed, traced onto the laminated cork, and bandsawed away to form the correct shape. This piece was then bonded with contact adhesive to the bridge, forming a complete sole.

Figure 5.6: 3M Fastbond water-based contact adhesive

The sole unit then needed to be shaped to the contours of the author's foot. An outline of the final shape of the sole was traced to the top of the sole, which was then bandsawed and sanded by hand using three different grits of sandpaper. Then, the heel counter was made from 3 layers of bamboo veneer and pressed against a semi-circulur mold inside the vacuum press.

The only part left to manufacture was the upper. A size 10 shoe last was purchased and taped up to create a stencil for the two pieces of the upper (tongue/vamp and quarters/heel). A sketch of the upper design was then drawn directly on the tape while it was still on the shoe last. After that, the tape was cut off and a stencil was created for the two pieces of the upper. The stencil was then digitized using Adobe Illustrator and a line art file was sent to the Princeton MAE machine shop's laser cutter to precisely cut out the hemp fabric in the right shapes. The fabric was sewn together using nylon thread because of its great strength and durability.

Figure 5.7: Bonded sole, pre-shaping

Using the last, the upper was formed and glued with contact cement to maintain a three-dimensional shape.

Hemp thread loops were sewn to the bottom of the upper to create the lacing system. After that, came the final step of using more contact cement and adhering the upper to the sole. The heel counter was also glued on with contact cement as the final touch. Shoelaces were obtained from the author's basketball shoes due to their color and length, which ended up working well with the finished shoe. The process was then repeated with a second shoe to create a matching pair.

Figure 5.8: Bonded sole, post-shaping

Figure 5.9: Heel counter

Figure 5.10: Shoe last, before and after taping

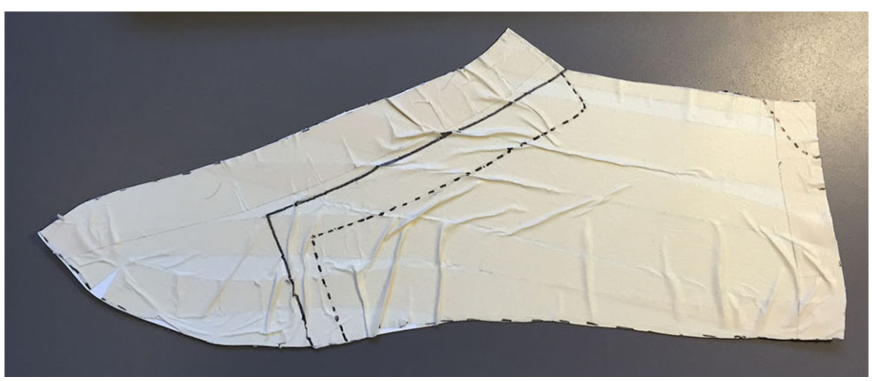

Figure 5.11: Shoe upper stencil

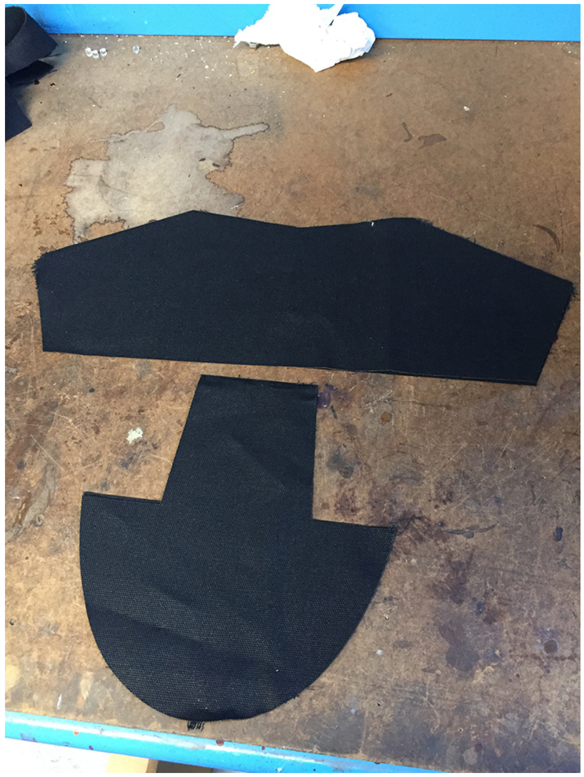

Figure 5.12: Laser-cut upper fabric

Figure 5.13: Shoe upper, stitched

Figure 5.14: Hemp thread stitched to the bottom of the upper

Figure 5.15: Completed shoe!

5.3 Testing and Simulating

5.3.1 Part Testing

One of the author's boat shoes was weighed against the bamboo shoe. The bamboo shoe came in at **11.9 oz** while the boat shoe weighed **12.7 oz**. The bamboo shoe therefore had a credible weight and was comparable to existing shoes on the market. The authors boat shoes was also made of thinner leather and had a shallow sole, making it very light as well.

Force testing was also completed on both the left and right finished shoes to determine how much deflection in the cantilever spring would occur under load. A mock "heel" was machined out of high density polyethylene (HDPE) and used in the Instron to press down as a heel would inside the shoe as shown in Figure 5.19. Both heels were able to compress down until the top of the spring made contact with the bottom. In the left shoe, a maximum load of **200 N** was achieved before the spring bottomed out. This was a staggeringly low number compared to the 1557 N the spring would ideally be able to deflect under. In fact, the author standing still in the shoes would put the force at approximately 650 N, of which 200 N is not even 1/3. The right foot fared much better, with a maximum load of **596 N** before bottoming out. This is still under 650 N, and the heel would bottom out with the author standing still in them, much less running with forces at 2.4 times body weight.

5.3.2 Finite Element Analysis in Creo Simulate

FEA was once again performed on the cantilever spring. With steel, this design reached a maximum stress of around 112 MPa, about half of what was in the previous iteration. With bamboo at 0.3 inch thickness, the simulation suggested that the new design would also fail with stresses at double the MOR of the laminate.

A sensitivity study for the thickness of the spring was conducted, and the following optimization showed that the spring would need a thickness of **0.47 inches** before the stresses went below the MOR. This implies that if the heel was thickened by laminating more layers and the 1 inch gap was maintained, the heel would be almost 2 inches tall. A cantilever spring at this thickness would be very cumbersome, difficult to manufacture, and potentially suffer aesthetically.

Another sensitivity study was done for the length of the cantilever, which if shortened, would reduce the moment arm and thus minimize stress in the material. However, the optimization was unable to find a length that would not cause the stress to

Figure 5.16: Bamboo shoe, 11.9 oz

Figure 5.17: Author's boat shoe, 12.7 oz

pass the MOR limit. Even at an unrealistic and comical 1 inch length, the cantilever spring still experiences stresses in the 60s MPa (Figure 5.25).

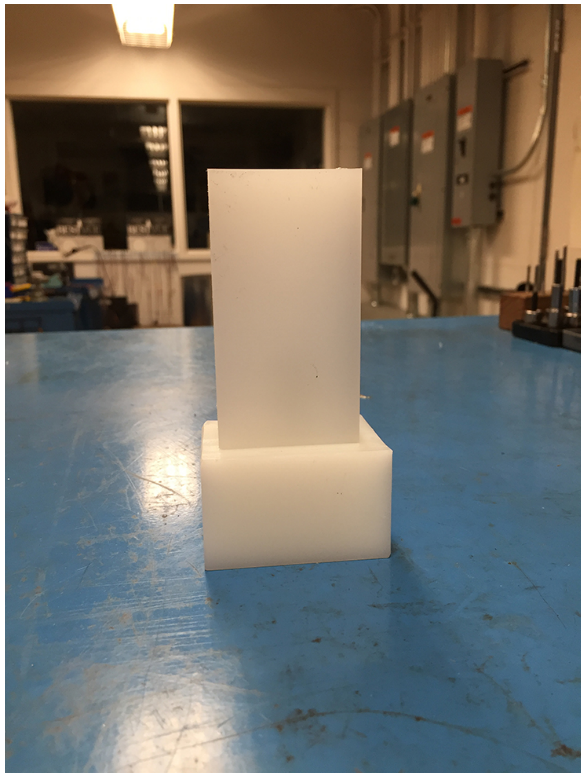

Figure 5.18: Heel force testing unit

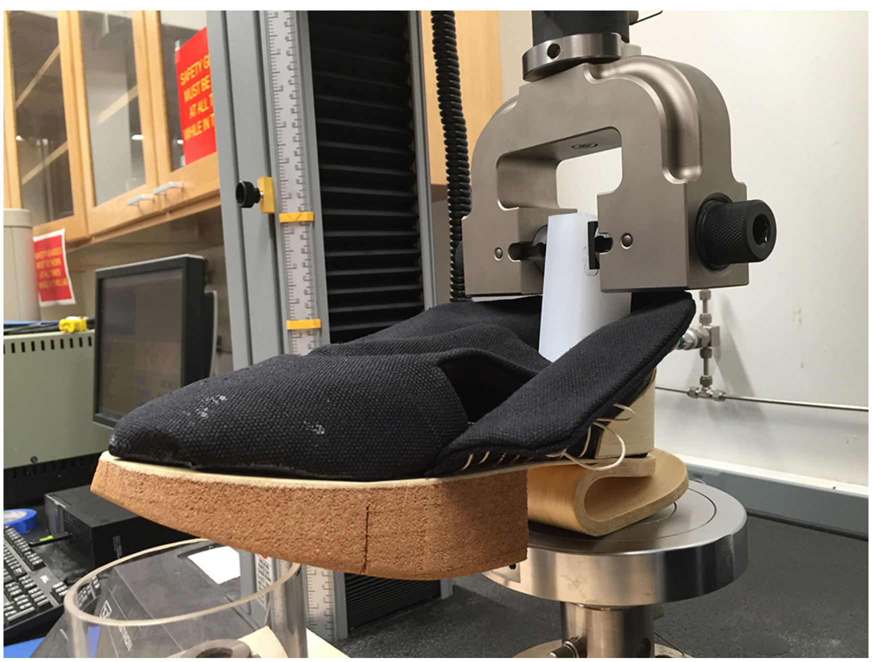

Figure 5.19: Testing the flexibility of the spring

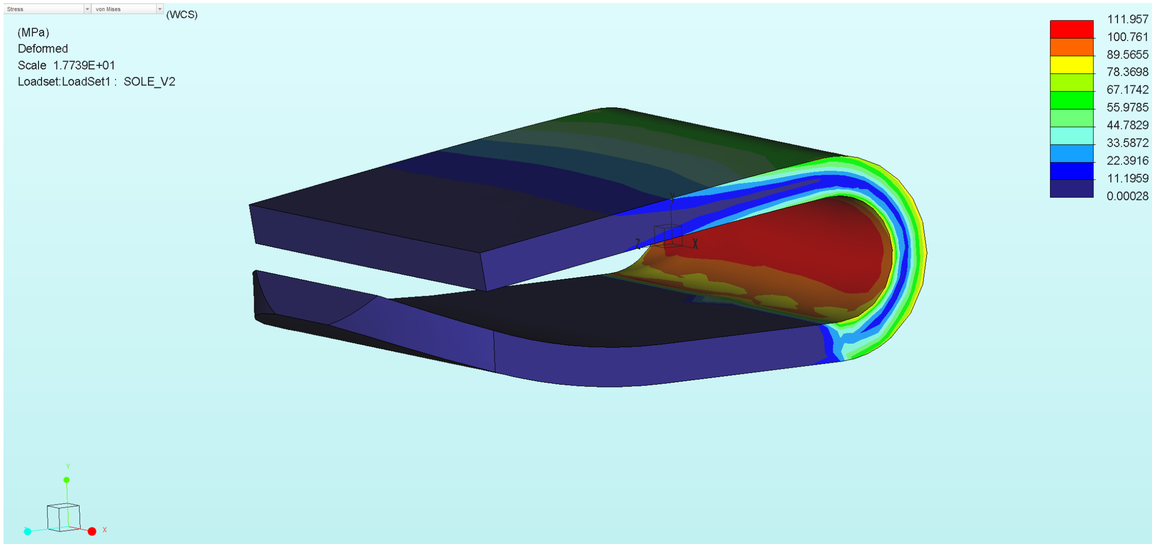

Figure 5.20: Simulation with steel

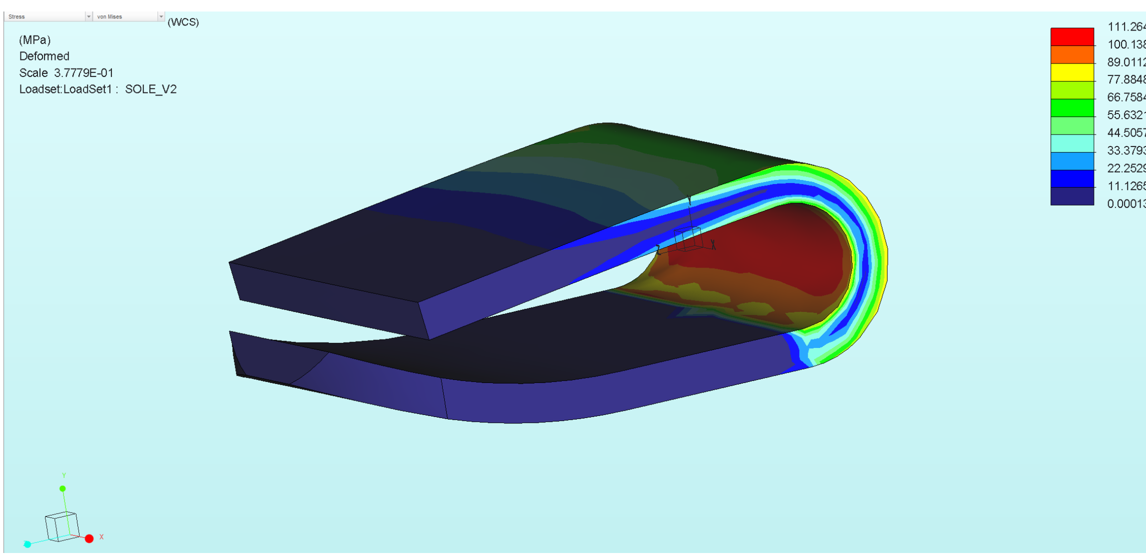

Figure 5.21: Simulation with bamboo

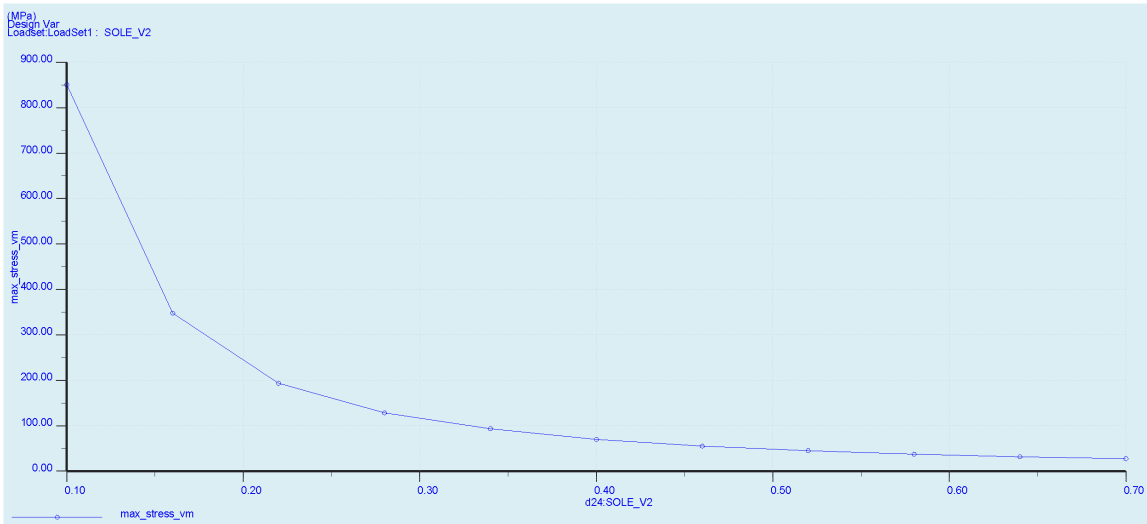

Figure 5.22: Spring thickness sensitivity

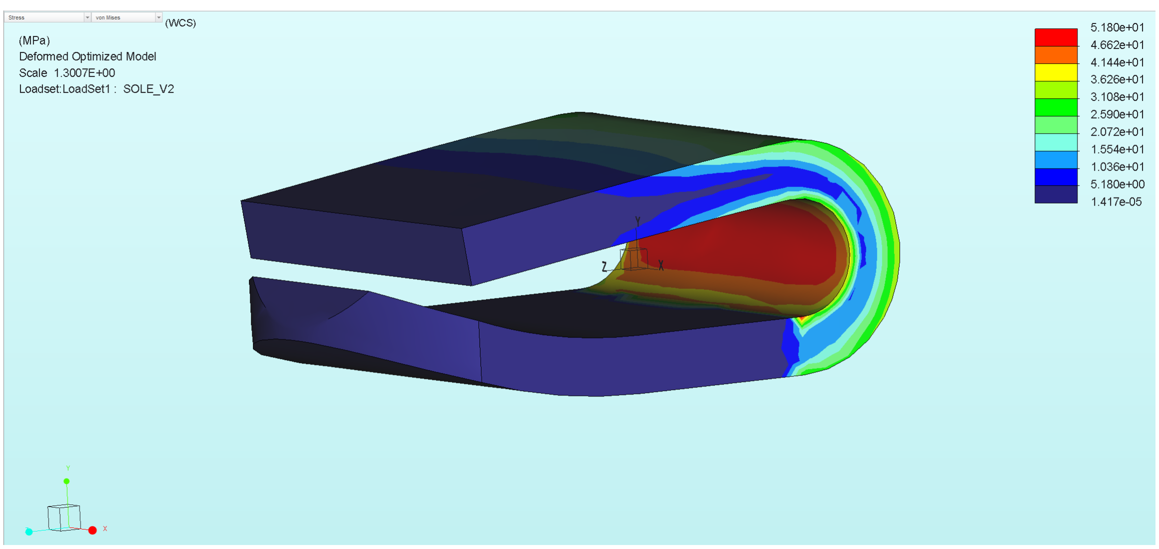

Figure 5.23: Spring at optimized thickness of 0.47 inches

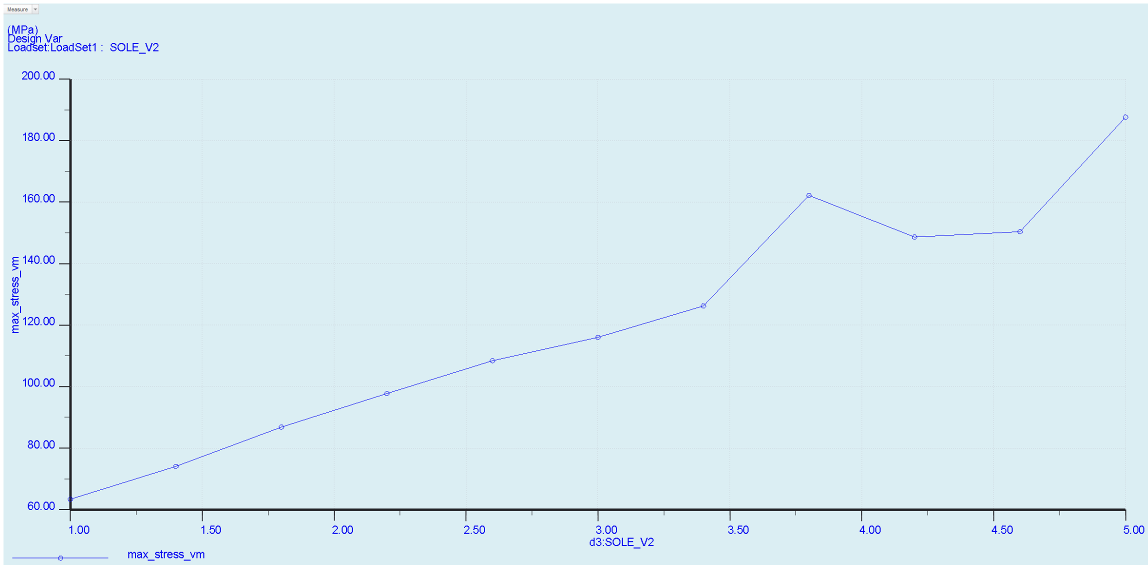

Figure 5.24: Spring length sensitivity

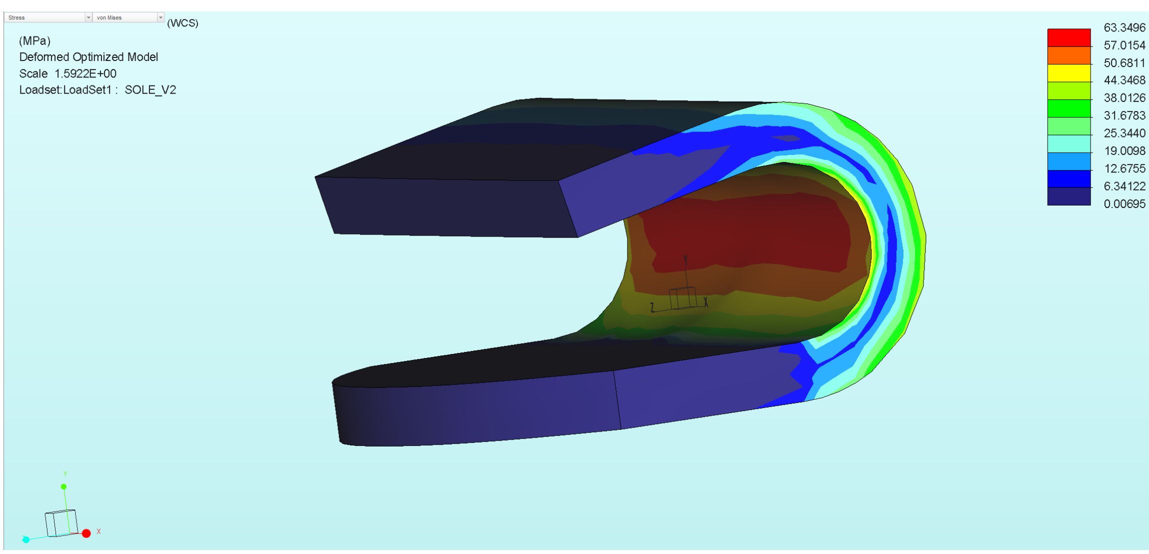

Figure 5.25: Spring at an unrealistic 1 inch length, still unable to reduce stress under the MOR

5.4 Obstacles

Based off of both force testing and FEA simulation results, the shoes manufactured by the author would be unable to hold up under the stresses of running. While doing a field test of the shoes, the author was able to walk in them with ease and no known failures in the materials occurred. Feeling confident, the author then decided to jog gingerly in them with no problems yet once again. The fact that the cantilever did not fail in this scenario may suggest that there other factors which could affect the efficacy of the shoe design.

For one, the author may have subconsciously landed at the midfoot or front-foot while jogging and relieved the heel of major forces. In addition, the author felt the heel bottoming out, even when walking, and the inelastic collision of the spring against itself may redistribute forces differently in the material and prevent it from failing.

During manufacturing, defects as shown in Figures 5.26 and 5.27 were present. The curve of the cantilever continued to be a problematic area. The molding process may put a lot of stress in that area and unless the right amount of pressure is held there during glue curing, the layers may tend to separate due to their desire to spring back to a flat shape. The separation between layers in the curve explains why the cantilever springs were much more compliant than expected. The layers would be able to slide against each other without any glue holding them together. In addition, separation creates air pockets that provide no resistance when the material is put under a load. A force will meet no resistance for the duration that the air pocket is being compressed. Until the materials at either side meet each other, it will literally feel like pushing air.

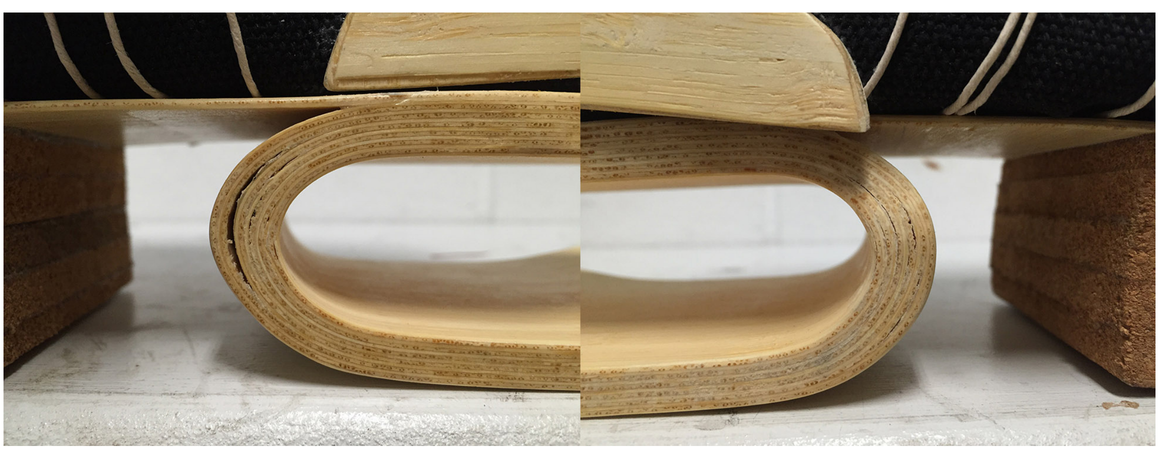

Figure 5.26: Manufacturing differences and slight defects

Figure 5.27: Layer separation at the curve

Chapter 6

Future Improvements and Conclusion

While the results of this thesis cannot vouch for laminated bamboo cantilever springs as a superior mechanism to elastomeric foams in conventional running shoes, there are still many reasons to believe that, with more research and testing, a feasible and effective running shoe design can be conceived from bamboo and other wooden material. Only two designs were tested over the course of this thesis, though there are an unpredictable number of others out there that could come to fruition.

In addition, only bamboo was used to create the cantilever spring. Other woods, such as maple and birch, merit experimentation in both the designs presented in this thesis as well as other ones yet unexplored. Characteristics beyond MOE, MOR, and density could prove other woods to be more appropriate than bamboo for use in a sole. For example, grain direction turned out to be a huge but unanticipated constraint with bamboo veneer. The veneer is constructed from strips of bamboo laid next to each other and unless for the fleece backing, the 0.6 mm thickness bamboo veneer would have easily split apart back into those constituent strips. Therefore, the bamboo's strength really only ran in the direction of the grain; any forces perpendicular to that would render the material useless.

At the end of the day, the shoes were able to bear the weight of the author while walking and even light jogging without breaking, even though the spring was too forgiving and consistently bottomed out with each step. Therefore, even a slight improvement in stiffening the spring, be it through better manufacturing techniques, the use of other materials, or altered design, would yield promising results.

6.1 Considerations for Future Experimentation

For continued exploration of wooden running shoe mechanisms, the following points should be acknowledged:

- be wary of the natural variation within organic materials
- get some helping hands
- find or create better equipment
- source materials from various places
- test the durability of materials

The first point is a reminder that natural materials like wood will inevitably fail to maintain the same kind of consistency as man-made products. Knots, cracks, and other small defects in wood could affect the mechanical properties of a particular sample. Even from tree to tree in the same forest, different factors such as water intake and available sunlight will produce wood with varying characteristics, however slight they may be. As such, results from one test need to be taken with a grain of salt and reproduced multiple times for confidence.

The second point is from the author's personal experience with trying to build shoes for the first time independently. Many steps during manufacturing would have been easier or quicker if there were multiple people engaged. Laminating wood around curves, for example, is a difficult task to accomplish alone. Things often need to be held in one place while another requires work, and a pair of extra helping hands could do that just fine. In fact, the author believes that the layer separation that ails the curve in the cantilever spring could be minimized if a second person was applying pressure on that area while the rest of the cantilever spring was being smoothed out. Repeating processes, such as cutting out multiple pieces of veneer or sanding, could be completed in a quicker timeframe.

The third point is in regard to how having the right or better equipment for manufacturing could lead to better results. While the one-sided foam mold worked relatively well for lamination, a double-sided mold made from even denser material that sandwiched the lamination together from both sides during curing may have also prevented manufacturing defects. In addition, a drum sander would have made shaping the soles much easier and faster than using a Dremel, which could be difficult to control, and hand sanding.

The fourth point is related to the first. Materials, such as bamboo veneer or cork, should be purchased from various sources in differing locations in an effort to account for potential variability in regional products. Cork grown and processed by one company, for example, may be softer than that from another. This would prevent experiments from potentially reaching premature conclusions.

The fifth point is important, especially for wood. Even if a excellent design were to be discovered, the time-dependent characteristics of a wooden mechanism in a shoe would be important. A shoe needs to be able to endure not just one, but multiple of the same high-magnitude load during even a short run. Frictional forces will also cause the wood to wear down through scraping if it is in direct contact with the ground. In a shoe made of foam, foam being worn away will simply cause a thinner sole that may end up being ineffective at attenuating shock. In a mechanical wood system, on the other hand, parts being worn away may cause sudden catostrophic failure and render the shoe immobile.

6.2 Potential 3rd Design

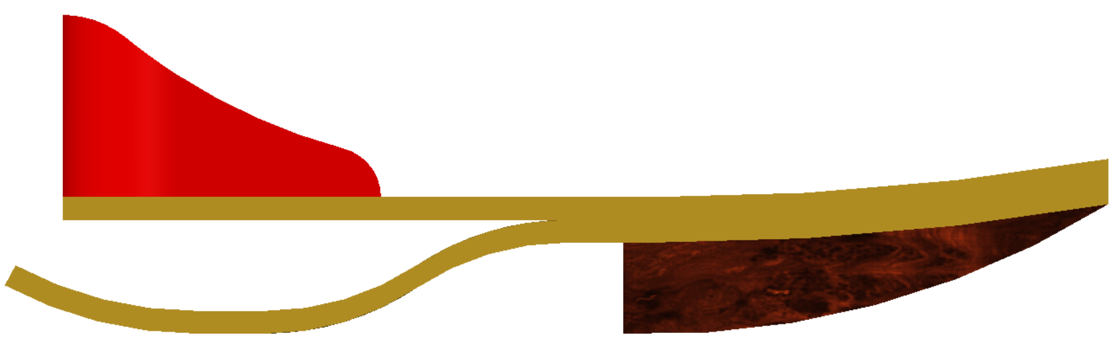

Figure 6.1: A potential 3rd design (side view)

In addition to the two iterations explored, a third concept was created and modeled in Creo that the author did not have the opportunity to create, as shown in Figure 6.1. The primary difference between this third design and the other two is a lack of a curved cantilever spring. Rather, two pieces of laminate are glued together at the forefoot in a shape reminiscent of a pair of tweezers or a wishbone. The advantage of this design is that the difficulty of producing the curve of the other two designs will be nonexistent. Adhering two flat faces is a much simpler task. In addition, the gap between the bottom and top laminates is no longer limited by the radius of curvature of the bamboo. Now, the gap can be made as narrow as possible to lower the wearer's center of gravity and provide both more comfort and stability.

The one downside with this design, however, is the thickness of the joined laminate at the forefoot. This area will be twice as thick as elsewhere and could have serious consequences for flexibility and liftoff. A dramatic toe spring may yet again be required as in the first design. Otherwise, this design appears to be an easier to manufacture version of the 2nd design, maintaining the cork midsole and heel counter.

6.3 Conclusion

Running shoe technology is constantly changing. Companies left and right are always introducing new ways of making oneself a better athlete. While there is certainly no shortage of innovations, most, if not all, in recent times are granted by the petrochemical industry. Though seemingly counterintuitive and maybe even anachronistic in the 21st century, paying closer attention to how a material like wood could (literally) propel us into the future could yield the next big thing. Wood has the ability to store incredible amounts of energy through flexure, as evidenced by bows and longboards. Its beauty and aesthetic quality are highly valued. These two facets combined sound like the perfect description for a modern running shoe.

Figure 6.2: The author enjoying his new bamboo shoes

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