Environmentally Friendly Sneakerboot Shanks and Their Effect on Aerobic Performance and Human Walking Gait

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Executive Summary:

Foreword:

The purpose of this research study was to investigate environmentally friendly replacements for the nylon shanks embedded in Forsake “Trail” sneakerboots. The first step in this process was determining which materials to investigate as a replacement for nylon. This research study has been conducted by Adam Ashcroft, a senior mechanical engineering student, with advising from Professor Ronald Bucinell. Desirable properties for shanks include stiffness, puncture resistance, fatigue resistance, and shock attenuation. Thermoplastic carbon fiber, flax, and bulk molding compound shanks were fabricated in this study. The thermoplastic and flax shanks were successfully manufactured, however the fibers in the bulk molding compound shanks did not properly bond together.

Hiking requires extended periods of aerobic activity. This day long activity can burn upwards of 2,000 calories for a 195-pound male. While numerous studies are available that investigate the aerobic performance increases from altering the midsole foam of an athletic shoe, minimal research has been conducted on the material of the embedded shank. Maximizing the walking efficiency by improving the shank material in a hiking boot can suppress fatigue and reduce the total amount of energy consumed. The following questions were answered in this study:

1) Does a stiffer shank material result in lower heart rates on a 0.75-mile, flat course?
2) Does a stiffer shank material result in lower heart rates on a 0.5-mile, 15% grade course?
3) Does a stiffer shank alter the walking gait of the wearer with respect to the wearer’s ankle pronation or angle of foot dorsiflexion?

The purpose of this report is to state the conclusions found in this investigation. Recommendations will be made to Forsake as for which shank is the best option to implement across their line of products. This research has implications beyond the scope of sneakerboots – high performance renewable composites can be implemented into a multitude of athletic products.

Summary:

The problem this report is concerned with is whether the material of a hiking boot's shank effects the aerobic performance, ankle pronation, foot dorsiflexion, and wearer comfort.

Results of Investigation:

A 195-pound male subject performed two heart rate tests for each combination of shank material and treadmill incline. It was found that 12 ply carbon fiber shanks reduced the ramping time of heart rate in a 15% grade treadmill slope but result in a heart rate that plateaus at 180 beats per minute – the same plateau as nylon and flax shanks. Shank material was found to have a limited effect on walking gait, however, an increase in treadmill incline resulted in an increase in the subject's ankle pronation.

Conclusions and Recommendations:

1) The 12 ply carbon fiber shanks have a longitudinal stiffness of 289,383 N-mm^2, the 9 ply carbon fiber shanks are 171,304 N-mm^2, the flax shanks are 39,513 N-mm^2, and the nylon shanks are 28,007 N-mm^2.
2) The heart rate of the wearer was lower throughout the 0% grade treadmill test for the stiffer carbon fiber shanks.
3) The heart rate of the wearer ramped up slower in the 15% grade test when the subject was wearing boots with 12 ply carbon fiber shanks in them.
4) Shank material has a minimal effect on ankle pronation and dorsiflexion of the wearer's foot.
5) Increasing the grade of a treadmill increased the severity of pronation in the test subject's ankles.

Based on the findings in this report, it is the recommendation of the author of this paper to continue to fabricate Forsake sneakerboots with nylon shanks until the results of this study are verified through further testing. It is a marketing advantage over competitors to use high performance materials in the boots. If future tests verify these results and a sizable waste stream from a composite manufacturing company can be tapped into, investigating methods of mass producing carbon fiber shanks with the intention of installing them in sneakerboots should be pursued.

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Introduction:

Shanks are rigid members embedded in the midsole of footwear articles to increase wearer comfort. Different types of footwear value different shank parameters. While a work boot requires a very stiff shank with immense puncture resistance (usually steel), a leather dress shoe only requires a shank to maintain the shape and aesthetic design of the shoe (usually either steel or hardwood). In this project, three shanks have been fabricated for the use in Forsake (a small footwear company founded by two Union College alumni) “Trail” model sneakerboots.

Sneakerboots are a hybrid between a casual sneaker and a hiking boot; they need to be comfortable whether the user is trekking up a rugged mountain or walking on a smooth floor. Due to the large variety of situations a sneakerboot is subject to, the sneakerboot’s shank needs to be equally as versatile.

Currently, Forsake utilizes nonrecyclable, flexible nylon shanks in their “Trail” model sneakerboot. Forsake Co-Founder and COO, Samuel Barstow emphasized the main goal for Forsake’s product line is comfort. To provide comfort to the wearer, a sneakerboot needs to remain puncture resistant while traversing jagged terrain (preventing the foot from arching unnaturally), it needs to be lightweight, it needs to absorb harmful shocks associated with large foot impacts, and it needs to provide ample energy return to the wearer per footstep. Increasing the energy return of the hiker will decrease long term fatigue throughout a day of activity and will subsequently increase the range a hiker can trek. The attenuation of harsh foot steps to the ground reduces the likelihood of soreness after an extended period of walking or running [1]. In addition to the listed performance improvements, designing and fabricating an environmentally friendly shank offers Forsake a marketable advantage over its competitors.

Heavy duty, backpacking hiking boots mostly utilize steel shanks, while day trekking boots use either nylon, fiberglass, wood, carbon fiber, material hybrids, or no shank at all (Figure 1). Steel shanks provide exceptional rigidity to boots; they can however result in a fatigued foot after extended periods of walking if the natural flexion of the metatarsophalangeal (MTP) joint is restricted [2]. The MTP joint connects the Metatarsal to the Phalanx (Figure 2) and acts as the natural fulcrum for the foot. A repeated interruption of this natural toe bending leads to discomfort.

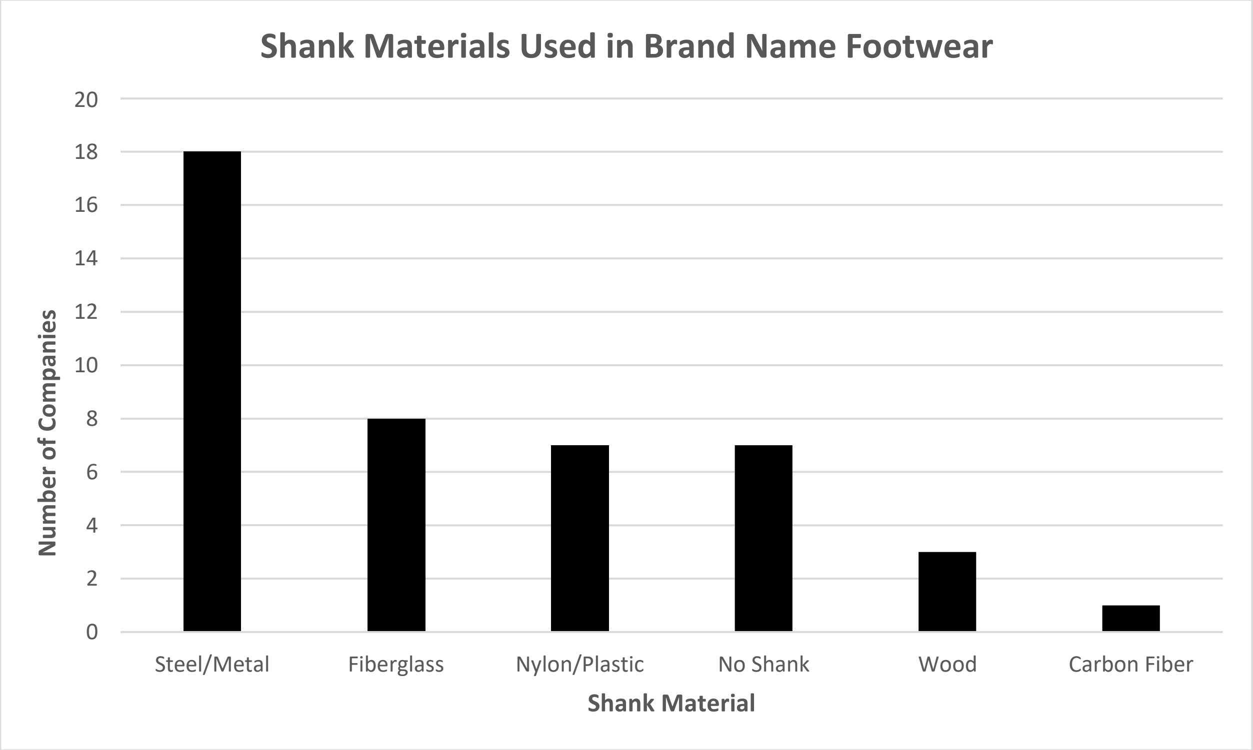

Figure 1: The data in this figure is provided from a 31-company questionnaire with the goal of determining the industry standard for the material used in footwear. Several companies use a variety of shanks in varying product lines, while others use no shank at all. Notable companies include L.L. Bean (steel), Timberland (steel, fiberglass, and nylon), and Clarks (steel, plastic, or no shank). The full list of companies can be found in ***Appendix 1****.*

Figure 2: A drawing of the location of the MTP joint. The MTP joint acts as the fulcrum of the foot and requires a balance between proper support and uninhibited flexion [3].

Nylon, fiberglass, and other combinations of materials can have the opposite issue associated with steel shanks – a lack of rigidity. A lack of rigidity when traversing small obstacles on a path can subsequently lead to arch pain in the foot. It is common to experience arch pain when traversing cobblestone or tree roots (two obstacles that a sneakerboot would often encounter). If the MTP joint is overextended (when walking up a steep hill for example) this can also cause discomfort in the MTP toe joint commonly known as “turf toe”. Turf toe is usually coupled with a long period of dorsiflexion, a biomechanical positioning of the ankle also associated with uphill walking (Figure 3).

Figure 3: The dorsiflexion of an ankle is of particular interest in this study. While traversing an uphill slope, the ankle will naturally be in a position of dorsiflexion (left). Energy return of a sneakerboot will be most significant in this scenario, as more energy is required to climb uphill than to hike on a flat path [3].

Along with MTP joint flexion, the pronation of a hiker's ankle is important to their fatigue level. Pronation and supination are phenomena that describe the rear-view angle of the ankle joint while a hiker's foot is in contact with the ground. Pronation of the right ankle is when the ankle overhangs the inside of the foot (closer to the left leg) [4]. Supination of the right ankle is the opposite effect – when the ankle overhangs the outside of the foot (away from the left leg) (Figure 4). Pronation and supination can severely increase the likelihood of ankle rolls and other leg injuries – if a stiffer shank is implemented in the boot it may be possible to reduce these walking habits. This study will utilize slow motion video to analyze each of the shanks' effects on walking gait and pronation tendencies.

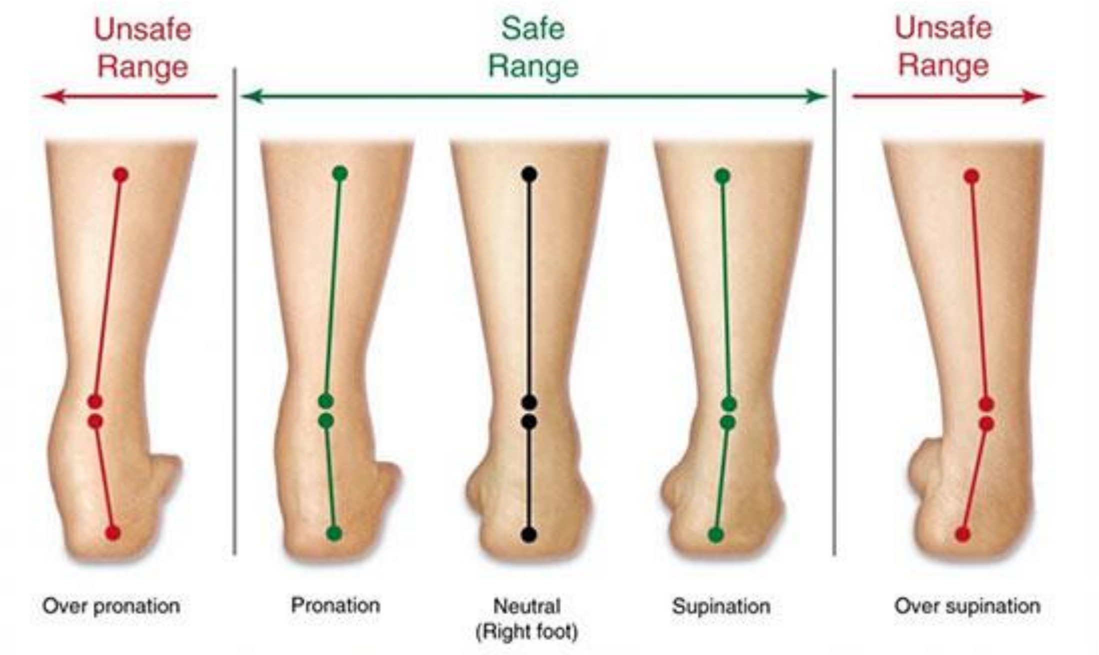

Figure 4: The phenomena of pronation and supination are illustrated above [4].

Energy return and shock attenuation are two metrics that directly affect the fatigue level and soreness of a hiker. If the shank of a sneakerboot is designed to store potential energy while it deforms (as the foot applies force to the ground) and releases the energy when removing the foot from the ground, the biomechanical efficiency of the hiker would improve as a result.

Research Implications to the World:

Every year in the U.S.A. and E.U. alone, 10 million tons of plastic are disposed of [5]. While adjusting the material of a growing sportswear company's sneakerboot shanks from plastic to a biodegradable or recyclable material will not solve this issue completely, there is a wasteful mindset of first world countries that needs altering. This small step in innovation for Forsake, if the environmentally friendly shanks are deemed worthy of mass production, will give their company a competitive advantage over companies who cannot boast their implementation of renewable materials. In a market that is heavily reliant on advertisement, Forsake can benefit from abandoning the traditional way of doing things.

Project Objective – Testing Performance of Environmentally Friendly Shanks:

Forsake sneakerboots currently utilize nylon shanks in select product lines. The decision by Forsake to have a nylon shank in their sneakerboots has gone unquestioned since the "Trail" sneakerboot's original design. It is the goal of this design project to determine the optimal environmentally friendly material for use in the "Trail" model sneakerboot.

Having an environmentally friendly shank is an important functional requirement in this design project. Nylon (due to its complex chemical structure) is a material that is very hard to recycle and will not biodegrade in a landfill [5]. There are three avenues for decreasing the environmental impact of shank fabrication: biocomposites, recyclable thermoplastic resins, and bulk molding compounds (BMC). Biocomposites (composite materials from sustainable, organic sources) are an alternative to nylon due to their biodegradability [6]. Promising biocomposites for this project include flax fibers and coconut coir because of their mechanical properties (Table 1). Another method of achieving environmentally friendly composite shanks is to use thermoplastic resins. Thermoplastic composites can theoretically have their matrix and fibers separated by means of melting the matrix. A final approach to making shanks environmentally friendly is to use a BMC comprised of scrap material that would otherwise be deposited in a landfill by a mass production company. The fibers of waste material can be chopped into a resin infused slurry and pressed into a shank to achieve comparable physical properties to a composite with traditionally oriented fibers.

Table 1: The physical properties of different materials are provided. Note the high specific strengths of the composite materials in comparison to steel and nylon. [6].

Material	**Density (g/cm^3)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Specific Tensile Strength (MPa*cm^3/g)**
Nylon 6/6	1.15	82	2 – 3.6	71.3
Steel, AISI 1045	7.7 – 8.0	585	205	73.1 – 76.0
E - Glass Fiberglass	2.58	1950 -2050	93.8	755.8 – 794.6
Thermoplastic PEEK Carbon Fiber	1.7	2400	146	1411.8
Thermoplastic PEEK Carbon Fiber BMC	1.7	288.9	43.4	169.9
Flax	1.5	345 – 1,100	27.6	230 – 733.3
Coconut Coir	1.15	131 – 175	4 – 6	113.9 – 152.2

It is important for shanks to have a longitudinal stiffness that allows for natural flexion of the MTP joint *and* provide ample puncture resistance when traversing a tree root. A comparison of longitudinal stiffness of the legacy nylon shanks to that of a carbon composite, flax composite, and balsa composite is provided in the Results/ Discussion portion of this report. The ISO standard for longitudinal stiffness (ISO 18896) is used in this study to provide consistent testing procedures with industry competitors.

The fatigue resistance of a shank is also a vitally important metric to measure. A shank that can withstand repeated loading equivalent to what would be experienced while hiking uphill is an obligatory functional requirement. If a shank were to fail due to fatigue, the wearer would lose all the benefits of the shank (puncture resistance, longitudinal rigidity, and energy return of the shank).

The final constraint of the shanks in this project is their cost. Forsake currently pays 10 cents per pair of sneakerboot shanks. Materials such as thermoplastic carbon fiber are commercially available on the magnitude of $100 per pound. Clearly this would not be a cost-effective approach to take, so a carbon fiber waste stream from a large producer would need to be tapped into to make this option feasible. Flax composite is also very expensive per unit area due to its low available quantities.

Three tests will be used to analyze the performance of shanks in this study. The first test (explained in Procedure 2 of this report) is measuring the individual stiffness of each shank using the ISO 18996 standard. This test will provide researchers with a repeatable method to determine the shanks' stiffness prior to their installation in Trail sneakerboots. The second test in this report is measuring the heart rate of an individual on flat ground and with a slope. This performance test is discussed in more detail in Procedure 3 of this report. The third test is the analysis of the walking gait of the test subject. Measuring angle of MTP dorsiflexion and ankle pronation is important to study whether the shanks influence the walking gait of the test subject.

Method of This Report:

The remainder of this report is divided into the following sections: background, design specifications, feasibility discussion, experimental procedures, theory and analysis, discussion of results, synthesis/ conclusions, recommendations, references, and appendices.

The background portion of this report is a comprehensive description of previous work on shanks. The design specifications portion of this report presents specific requirements for the design of Forsake sneakerboot shanks. The goal of the feasibility discussion is to show the reader the narrowing down process applied to the design concepts based on engineering intuition, cost, and required resources. The experimental procedures section of this report describes the test methods used in this study. Following the experimental procedures are the theory and analysis section of the report. This section describes the theory behind the testing and what the expected results are. The results of the tests will then be provided in the discussion of results section. This section both displays the experimental results and provides an explanation of them. Finally, the synthesis/ conclusion and recommendations sections summarizes the entire report and provides a recommended course of action for Forsake.

Background:

This section of the report is comprised of five subsections. The first subsection will discuss the components of a hiking boot. The second subsection discusses the shank materials to be used instead of the legacy nylon product. Third, the environmentally cautious manufacturing method of hot pressing will be discussed. Fourth, the desired shank and sneakerboot performance specifications will be presented. Finally, a functional decomposition of a sneakerboot shank will be discussed.

Components of a Hiking Boot/ Sneakerboot:

There are several types of hiking boots. Heavy duty mountaineering boots are beyond the scope of this project – these boots typically are very insulative, stiff, and are meant for alpine expeditions. Backpacking boots are a step below mountaineering boots in terms of ruggedness. Finally, the style of hiking boot that is most like the Forsake “Trail” sneakerboot is a day hiking boot. Day hiking boots can supply ample support to the foot on a mountain trail but are also versatile enough to be worn in public. Components of a day hiking boot are provided in Figure 5.

Figure 5: This annotated picture comprehensively shows the components of a hiking boot. The shank (which is hidden in the midsole of the boot) is represented with the red line. The midsole of the boot is responsible for a majority of shock damping when walking or running. The tip of the boot is a durable rubber that is tear and abrasion resistant. The upper of the boot (not labeled) is the main fabric or leather. Within the upper of the shoe is typically a series of waterproofing materials to keep the foot dry.

Green Materials:

The environmentally friendly materials used in this study are broken down into three categories: biocomposites, thermoplastic composites, and bulk molding compounds.

Biocomposites are materials consisting of biodegradable polymers as the matrix material and a biofiber as the reinforcing element [6]. Biocomposites have the benefit of maintaining comparable mechanical properties (Table 1) to traditional composite materials while having the environmental benefit of biodegradability. Common biocomposites include flax fibers, coconut coir, jute fibers, and hemp fibers [6]. Biocomposites can be used as a replacement for traditional composite materials in applications that do not quite require the performance of carbon fiber or fiberglass.

Thermoplastic composites are classified because of their recyclable thermoplastic matrix material. Thermoplastics, rather than curing like a resin or epoxy matrix, simply melt when heat is applied, and solidify to their new shape upon cooling. This recycling property can theoretically be repeated numerous times. In addition to thermoplastics' recyclability, thermoplastic matrices have physical properties superior to thermoset resins. These benefits include: superior fatigue resistance, superior toughness (a property that lends itself to puncture resistance), and self- healing (a result of reparability) [7]. While nylon, the legacy product used by Forsake, is also a thermoplastic, it is not degradable due to the tortuous entanglement of nylon’s polymers [5].

Another environmentally friendly composite material is a bulk molding compound (BMC). Bulk molding compounds employ randomly oriented fibers (typically 10mm long) infused in a slurry of resin [8]. This fiber/ resin slurry is then heated and pressed to form a more anisotropic material than traditional composites. While the product of a BMC is not recyclable itself, the fiber constituent can be recycled from scrap material that would otherwise be discarded. Lamborghini and Callaway are two companies on the forefront of BMC implementation – these companies coined the term “forged carbon” (Figure 6). The marketing department of Lamborghini is emphasizing this “revolutionary” forged carbon material used in their cars. A similar marketing approach can be used by Forsake if a BMC proves to be the best material for shanks. While BMC compounds prove to be beneficial in theory, their manufacturing is difficult. Several attempts to forge these composites were attempted in this study – each resulting in a debonding of the randomly oriented fibers.

Figure 6: Forged carbon (BMC) is used in the wing of the 2018 Lamborghini Huracan. BMC is used in composite applications where anisotropy is desired. The shiny luster of a BMC composite also provides a unique appearance in the supercar industry [9].

Flax is a suitable biocomposite for this study due to its comparable physical properties to that of fiberglass, and its availability in the Union College Composite Manufacturing Laboratory. The PEEK impregnated carbon fiber was selected due to its availability from Automated Dynamics, a composite manufacturing company located in Niskayuna, NY with a sizable waste stream. The material that would have ordinarily been thrown in a landfill by Automated Dynamics can be recycled. An added benefit of using these materials is the severely reduced cost (the PEEK carbon fiber was attained free of charge) from an off-the-shelf product.

Cost of Environmentally Friendly Materials:

From the results of an internet survey (Appendix 1), there are currently no large-scale companies that utilize biocomposites, thermoplastic composites, or BMC materials in boot shanks. After realizing the benefits an environmentally friendly composite can offer, it seems peculiar that none have been introduced to the shank industry. The most prohibitive reason for a lack of ecofriendly shanks in the market is material cost and material availability. While numerous patents have been filed (including reference [10]) claiming to have a revolutionary product that will change the footwear industry, material cost has restricted any of these concepts from becoming marketable. The PEEK impregnated carbon fiber material used in this study typically sells off-the-shelf for $100/ pound. A cost-effective approach in which waste streams of large companies are tapped into can be implemented to attain aerospace grade materials at a fraction of the commercial material cost.

Green Manufacturing - Utilizing a Pressing Operation:

In addition to utilizing green materials in this project, green manufacturing methods will also be exploited. Rather than manufacturing the composite shanks with the industry standard, autoclaving (Figure 7), a pressing operation will be used. For small composite parts of simple geometry, pressing operations have numerous benefits over autoclaves including: reduced cycle time (minutes for snap cure composites in a press versus hours in an autoclave), reduced capital investment ($2,000 for a hydraulic press and heat blankets versus $200,000 for a fully functional autoclave), and most importantly for this project - limited waste (pressing operations require minimal disposable plastic, if any) [11]. Presses also reduce the amount of floor space needed to manufacture an equally sized part.

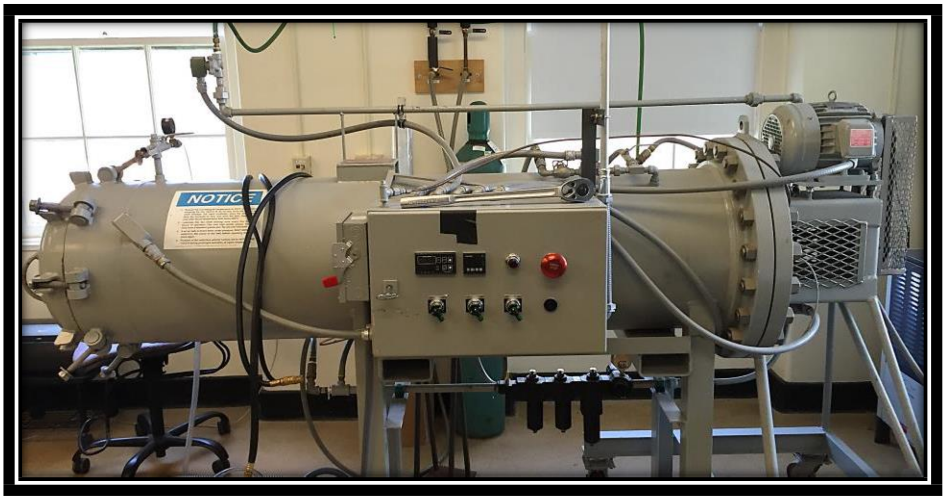

Figure 7: An autoclave is a pressurized oven used to fabricate composite materials. While uniform temperature and pressure are achieved in an autoclave, drawbacks include energy inefficiency, high capital investment, large form factor, wasting of bagging material, and slow cycle times.

Pressing operations achieve fast cycle times due to conductive heat transfer compared to convective heat transfer in an autoclave. Conduction is a more efficient means of heat transfer than convection because the heating element is in direct contact with the composite. Autoclaves, on the other hand, require the air inside them to be heated which in turn heats the composite part. Due to the inefficiency of the heat transfer in convection, autoclaves require an exorbitant amount of electricity to operate [11].

The waste associated with an autoclave is dramatic. For a proof of concept, two flax/ balsa hybrid composite shanks were fabricated in an autoclaving operation (Figure 8). Bagging material, bleed cloth, felt spacers, flash tape, and sealant tape are all non-recyclable materials that are disposed of after the composite is made. Pressing operations such as Vistex Composite's Specialized Elastomeric Tooling (SET™) do not require bagging material [11]. Instead, a chemical release agent is used to release the part from an aluminum mold.

Figure 8: Flax planks with a balsa core were fabricated to illustrate the wastefulness of autoclaving. The waste material (right) includes: bagging material, bleed cloth, flash tape, sealing tape, and non-stick plastic.

Performance Specifications for Shanks:

Two ISO standardized testing methods exist for shank performance: fatigue resistance and longitudinal stiffness (Table 2). The fatigue resistance of shank is important so the shank does not fail as a result of numerous day treks. It would be an exceptionally poor performing shank if a sample did not last more than three day hikes. ISO Test 18895 indicates a shank needs to withstand at least 60,000 cycles of a 49 N load, loading the shank at 4 Hz. ISO Test 18896 provides a test method for repeatable measurement of a shank's longitudinal stiffness. Longitudinal bending stiffness, as the functional requirement portion of this section will explain, is the most important characteristic of a shank.

Table 2: ISO standards are recorded for fatigue resistance and longitudinal stiffness for footwear shanks.

Test Method	Property	Requirement/ Goal
ISO 18895	Fatigue Resistance	Over 60,000 cycles
ISO 18896	Longitudinal Stiffness	Over 1,200 kN mm^2

Functional Requirements of Sneakerboot Shanks:

Sneakerboot shanks have several functional requirements: prevent punctures, optimize midsole rigidity, increase wearer's aerobic economy (heart beat and oxygen consumption), and attenuate shock from harsh footsteps. Each of the listed functional requirements have a common goal for the sneakerboot – enhance comfort of the hiker.

Traditionally, puncture prevention is accomplished in footwear with a steel plate or steel shank. Unfortunately, having a rigid steel plate or shank in a boot is proven to alter the gait of the wearer in a negative manor [12]. In a study on the effect of a firefighter's gait while wearing rigid soled steel shanked boots, results show increased instability of the wearer compared to stability in a sneaker. The study recommends a composite shank rather than a steel shank – composites can provide similar puncture resistance while reducing boot weight, reducing the wearer's physical strain, and reducing mechanical resistance [12]. Thermoplastic PEEK impregnated carbon fiber shanks could be a solution to this problem. Thermoplastic polymers are superior to thermoset resins in terms of puncture resistance, and they are also lighter than steel plates.

The rigidity of a sneakerboot needs to neither be minimized nor maximized – it instead needs to be optimized. An industry rule of thumb is to maximize an athletic shoe's stiffness until the natural motion of the MTP joint is interrupted [2]. An interruption of this natural joint movement can lead to foot fatigue, and long-term pain [2]. In contrast, activities that requires severe dorsiflexion of the foot (such as a football or steep mountain trekking) can cause turf toe if a sub-adequate stiffness is present in their footwear [13]. It is then, the job of the engineer to allow ample flexing of the MTP joint, while increasing longitudinal stiffness such that turf toe is not developed.

Flexural rigidity can be increased in two ways: altering the geometry of the shank (which in turn alters the moment of inertia of the shank) and altering the material of the shank. Since the shanks in this study need to be retrofitted into an existing product, a geometric change is not viable. Instead, a modification in shank material is the method of increasing shank rigidity until MTP flexion is interfered with. Materials discussed in the green materials portion of the background will be investigated as replacements for nylon in Forsake’s sneakerboots.

With this knowledge of a performance shoe’s flexural rigidity and MTP joint flexion, it makes sense that the aerobic economy of a hiker is also increased when longitudinal stiffness is optimized. Aerobic economy is defined as the amount of oxygen a person consumes during a cardiovascular activity like running or hiking [14]. A study from the University of Calgary shows that an increase in longitudinal bending stiffness (by means of an implanted carbon fiber plate) increased the aerobic economy of 13 subjects by an average of 1% [14]. While this study acknowledges that the longitudinal stiffness of a shoe causes an increase in aerobic economy, the mechanisms that attribute to this aerobic economy are still not completely understood.

Shock attenuation is a topic in footwear with extensive research. Similar to the rigidity of a boot (as seen with the firefighting example), shock attenuation is also only beneficial to a certain degree [14]. As the cushioning of the midsole is increased, stability of the heel decreases. At a certain level of cushioning, the benefits of shock attenuation are overcome by the instability of the athlete’s heel. Rather than adding support to the heel, an over cushioned shoe will deform and rock back and forth, causing instability for the wearer. This phenomenon can be visualized if one imagines running with kickballs under their feet. Shock attenuation is typically achieved in the rubber materials used in the midsole and outsole of a hiking boot. Incorporating a shock attenuating material as the core of a rigid carbon fiber composite could aid in damping vibrations that are harmful to joints [10].

Not dissimilar from most things in life, the functional requirements of a shank need to find a sweet spot. A puncture resistant shank is required; however, it cannot be so rigid that the wearer is not balanced properly. Having a shank that is too stiff will cause discomfort, as will a shank that is too flexible. While the aerobic efficiency is desired to be as high as possible, the metrics that play a role in it must be optimized, not maximized. This is also the case with shock attenuation – too much shock damping will result in a boot that is too cushioned and therefor unstable.

This project provides the opportunity to implant environmentally friendly shanks into the midsole of a sneakerboot. This opportunity will be fulfilled by fabricating several samples of each shank material and testing their longitudinal stiffness and fatigue resistance in accordance with ISO standards. When the different shank materials are characterized and compared to nylon shanks, the best performing shanks will be shipped to China for a factory installation into Forsake's Trail sneakerboot. After the shanks are shipped back to the United States, a series of hiking comfort tests will be conducted to subjectively analyze the comfort of the sneakerboots.

Design Specifications:

As stated in the background portion of this report, there are four functional requirements for a sneakerboot's shank to uphold. These functional requirements are: prevent punctures from harming the wearer's foot, optimize the rigidity of the sneakerboot's midsole, increase the wearer's aerobic economy, and to attenuate shocks that may cause leg joint discomfort. Each of these functions can be broken down into specific requirements.

Since the design of the sneakerboot's shanks is predetermined for fitting into the cavity of size

10.5 trail sneakerboots (123 x 23 x 2 mm rectangular prism), the material is the only variable in this design project. The fabrication process of the flax and carbon fiber shanks is almost identical – the only difference being the temperature of the hot press and the amount of time in the hot press. While the epoxy of the flax composite needs to cure, the thermoplastic PEEK simply needs to reach a melting point and mix with the molten PEEK of other layers.

Selection of Design Criteria:

Producibility is a major concern for this project. Shanks need to be produced rapidly to keep up with the growing demand of Forsake sneakerboots. Currently, the nylon shanks are mass produced in an investment casting operation – this produces a high quantity of identical parts. With both the carbon fiber and flax shanks, a pressing operation is the best choice for manufacturing. As described in further detail in this report’s Background section, pressing operations have numerous benefits over autoclaves. In early fabrication stages, the carbon fiber composite had the tendency to not stay laminated together when subjected to a bending load. A potential solution is to increase the temperature, pressure, and duration of the hot press.

Reliability of a design is also up utmost importance. Since the geometry of the new shanks are identical to the legacy product, the only concern with reliability is that of fatigue resistance. A shank that wears out and fails after a short walk through a shopping center is very impractical and should not be pursued. ISO 18895 claims that a shank should be capable of flexing 60,000 times under a 49 N load.

Feasibility Discussion:

The main decision points for the shank material of Forsake Trail sneakerboots are cost and material availability. While a small percentage price difference seems minor, one must remember that this inconsequential difference is multiplied by thousands of boots – quickly increasing the total cost of production. Currently, the nylon shanks used in Forsake's sneakerboots cost 10 cents per pair (five cents each). Nylon is also a readily available material, and it is likely that the supply of nylon will never be low enough to not fill the needs of Forsake's boots.

The off-the-shelf price of PEEK impregnated carbon fiber is $100 per pound. While this is an exorbitant amount of money, the carbon fiber used in this application would be sourced from a waste stream of another company. Because of this second-hand recycling, the cost of material would be severely discounted from its off-the-shelf price; it is possible for this material to even be free from a large enough supplier. The issue with the PEEK carbon fiber, then, is not the price, but rather the availability of scrap material that is large enough.

With the addition of flax or carbon fiber into the boots, Forsake will have a sizable marketing advantage over competitors. Having a high performing material in their shoe that no other company uses will also make their product objectively better. Forsake, as their name implies, is a company that goes against the conservative approach – they are not afraid to improvise and adapt to new technologies.

Because carbon fiber is more in the public eye as a high performance "futuristic" material, it would make sense for the carbon fiber shanks to be more marketable than nylon. Carbon fiber is used in other high-end sporting equipment (even some other high end running sneakers). Having a premium material in the sole of a boot would increase the value of the shoe beyond the added price of incorporating carbon fiber. For these reasons, it is the hypothesis of the author of this paper that the carbon fiber boots will outperform both flax and nylon. Combining the added performance of the carbon fiber to the marketing advantage it provides makes it the most feasible option for future Forsake sneakerboots.

Experimental Procedures:

There are four experimental procedures – the first procedure is the manufacturing of shanks, the second procedure is measuring the stiffness of the shanks, the third procedure is the heart rate testing, and the fourth is walking gait testing.

Procedure 1a: Manufacturing Thermoplastic Carbon Fiber Shanks

1) Clean two pieces of 12 x 12 x 1/8" aluminum plates with acetone and a razor blade. The plates should not have any residual epoxy, corrosion or surface defects prior to the composite layup.
2) Place one aluminum plate on a flat table top.
3) Using composite shears, cut strips of thermoplastic impregnated carbon fiber to 123mm in length, and 23 mm in width.
4) In the middle of the aluminum plate, three inches from the edge, stack the strips of carbon fiber. Stack an equal number of plies three inches from the other edge of the plate so there is symmetry. The number of strips placed down is the desired number of plies for the composite. In this study, two 12-ply composites were manufactured next to each other, and two 9-ply composites were manufactured in a subsequent hot press operation.
5) Carefully move the plate with two stacks of composite from the table onto the bottom platen of the Tetrahedron hot press. Be sure that none of the plies shift while transferring the plate.
6) Place the other aluminum plate on top of the composite stacks. The stacks will tend to shift while doing this, so it is very important to place the top plate down flat.
7) The melting point of PEEK plastic is 343 ^{o}C. The Tetrahedron hot press program to form the composites in this experiment was set at 430 ^{o}C, and 10 kips of force. The Tetrahedron hot press should be programmed to apply heat and pressure for 10 minutes – since the PEEK plastic is a thermoplastic, the heat and pressure simply need to melt the plastic. There is no entanglement of polymeric chains that there would be in a thermoset composite.

8) After 10 minutes of heat and pressure, program the temperature to ramp down at a rate of 10 degrees per minute. Ramping down the temperature of the hot press will reduce residual stresses in the shanks. Residual stresses are produced due to differences in thermal expansion coefficients of the PEEK plastic and the carbon fiber.
9) After a ramp down to 40 ^{o}C, the shanks are complete, and the Tetrahedron will open its platens.
10) Using a high speed Dremel multitool and a 1 mm diamond bit, drill a hole 1 cm from each end of the shank.

Procedure 1b: Manufacturing Flax Shanks

1) Clean two pieces of 12 x 12 x 1/8" aluminum plates with acetone and a razor blade. The plates should not have any residual epoxy, corrosion or surface defects prior to the composite layup.
2) Place one aluminum plate on a flat table.
3) Remove pre-preg flax composite from a freezer that maintains a temperature of -4 ^{o}C.
4) With the goal of manufacturing two shanks of dimensions 123 x 23 mm, cut eight pieces of flax composite to 300 x 60 mm. Cutting the flax into its desired shank dimensions will be done after the pressing operation.
5) Place a layer of high temperature release film on an aluminum plate from step 2.
6) Begin stacking the eight, flax lamina onto the center of the release film in a $[0/90]_{2S}$ orientation.
7) Around the perimeter of the release film, apply high temperature double layer tape.
8) Place another layer of high temperature release film on top of the flax laminate. Seal the two pieces of release film around the flax composite with the previously placed double sided tape.
9) Place the second aluminum plate on top of the composite, making sure that the composite is centered between the two plates.
10) Put the sandwiched aluminum plates in the Tetrahedron hot press. Program the hot press to apply 10 kips of force, and 200 ^{o}C to the composite for 30 minutes.

11) Like the carbon fiber composite, allow the temperature of the Tetrahedron to ramp down to 40 ^oC after the 30-minute entanglement period. This should be done at a rate of 10 ^oC per minute to minimize resultant stresses from cooling.

12) With the forming of the composite complete, the shanks can be cut into shape using composite shears.

13) Using a high speed Dremel multitool and a 1 mm diamond bit, drill a hole 1 cm from each end of the shank.

Procedure 2: Testing Stiffness of Shanks

Prior to testing the shanks inside of the sneakerboots, it is important to measure a standalone stiffness for a performance correlation. This test is in line with ISO Standard 18896: Testing Longitudinal Stiffness of Shanks.

1) ISO Standard 18896 calls for a cantilever bend test with variable masses suspended from one end of a shank. For this test the following materials are required: a means of measuring displacement with an accuracy to the nearest 0.5 mm, two 500-gram masses, an elevated surface, and a 20-kilogram mass to secure the shank in a cantilever orientation.

2) Sandwich a shank between the flat tabletop and 20 kg mass so that the drilled hole in the shank is roughly 90 mm from the edge of the table (Figure 9 below). Measure the exact distance and record the value.

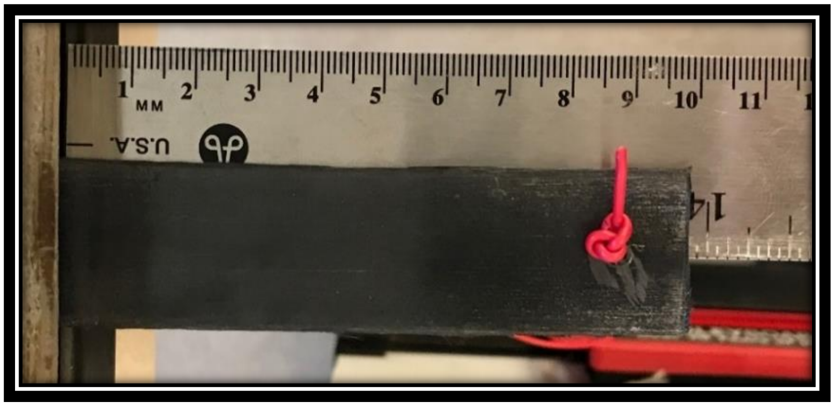

Figure 9: A 12 ply carbon fiber shank is having its cantilever distance measured (86 mm).

3) Loop a string or wire (an insulated wire was used in this study) through the 1 mm hole in the shank. Tie a knot on the top to prevent the wire from slipping through the hole (Figure 9).

4) Measure a control vertical displacement of the shank prior to measuring its displaced distance.

5) Add 500 grams to the hanging wire. Measure the new vertical displacement of the shank (Figure 10). Record this displaced value. Be sure to have a completely vertical ruler, measuring from the same reference height.

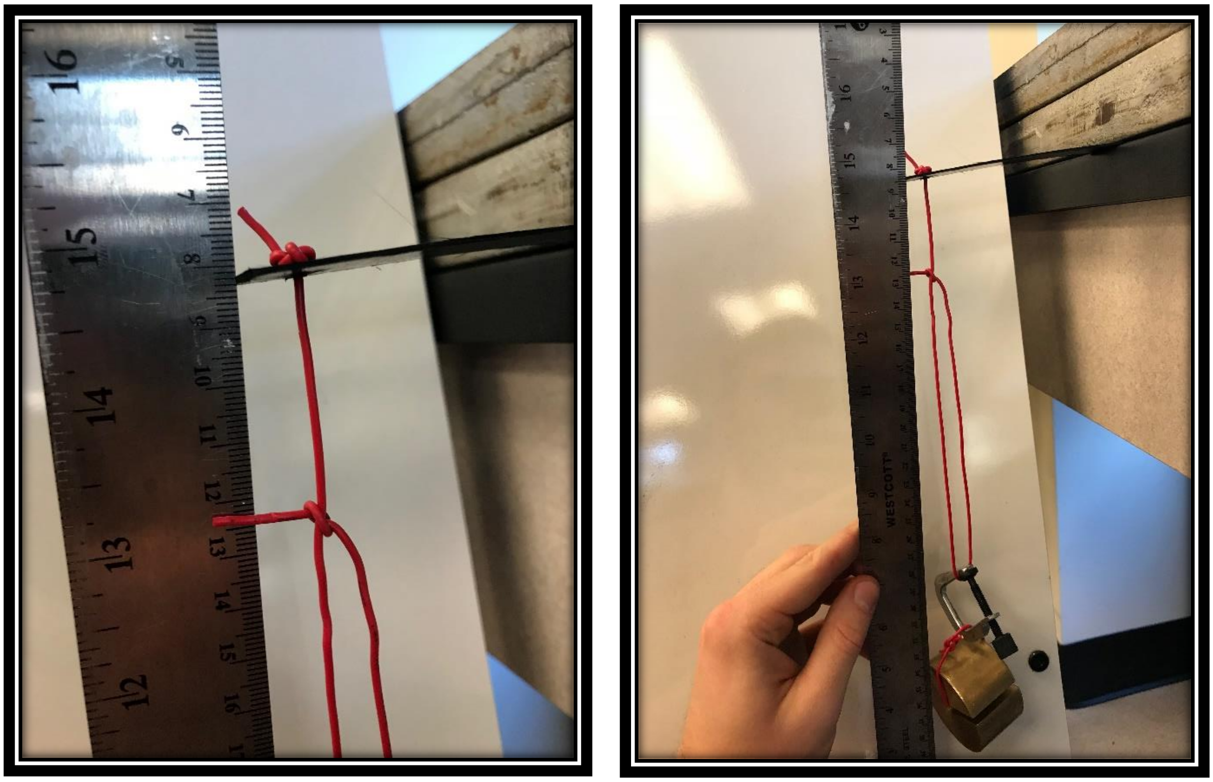

Figure 10: Measuring the vertical displacement of the shank after loading it with 500 grams.

6) Add a second 500-gram mass to the hanging wire and record the new displacement.

7) Repeat this procedure for each of the shanks.

8) Calculate the stiffness of the shanks using equation 1 for each load.

$$S = \frac{WL^3}{3a} \tag{1}$$

Where:
S = Stiffness (N-mm^2)
W = Load (N)
L = Moment Length (mm) ~ Procedure 2, Step 2
a = Deflection distance (mm)

9) Calculate the mean stiffness of each material shank.

Procedure 3: Measuring Cardiovascular Performance (Heart Rate)

Heart rate is closely linked to aerobic performance and oxygen consumption. For this reason, only a heart rate measurement was taken in this study of aerobic fitness. The following procedure will describe two tests that can be performed consecutively to save time.

1) Objectivity and sample size are important for measuring the performance of athletic equipment. Because of this, one must devise a factorial study that removes all subjectivity in testing of boots. This study did not use a sizable number of volunteers, so to improve upon the data collected, more test subjects should be used in future studies.
2) Prior to doing any aerobic activity, it is important to measure a baseline heart rate. Do this with the built-in heart rate sensors most treadmills have installed. Verify the treadmill's accuracy by counting the individual's number of heartbeats per second for 15 seconds and multiplying this value by four. Record the baseline heart rate.
3) The first of the two tests performed in a single day is the flat 0.75 - mile test. Set the treadmill to zero percent grade and 3.5 mph and begin walking.
4) Every 0.05 miles record the walker's heart rate. It is best to be hold the heart rate monitors for the entirety of the test except for recording heart rates.
5) Repeatedly record the walker's heart rates until 0.75 miles has come to an end.
6) After performing the zero-grade test, the individual must now relax until their heart rate returns to its previous base level (step 2).

7) When the heart rate of the individual plateaus at the original baseline (typically 15-20 minutes after test 1), increase the treadmill's grade to 15%.
8) Like the zero-grade test, measure the heart rate of the test subject through the monitors on the treadmill every 0.05 miles.
9) Due to the earlier onset of fatigue in the elevated test, a heart rate plateau is achieved faster. This test requires the participants to walk 0.5 miles.

Procedure 4a: Measuring the Pronation of a Subject's Ankles

Analysis of the pronation of the subject's ankles requires a treadmill capable of inclining to 15 % grade. This procedure also requires a video camera capable of shooting a minimum of 120 frames per second. A free video editing software (Lightworks) was used in this study to analyze results.

1) Position the video camera behind the treadmill such that it records the back of the subject's feet as he or she walks.
2) Start the treadmill at 3.5 miles per hour and zero percent grade.
3) With the treadmill running, position a makeshift clapperboard with the label of the test about to be conducted on it (write "12 Ply TPCF 15% Grade" for example). This practice will make editing the video much easier when the thumbnail of each video is what test was conducted.
4) Begin recording on the camera.
5) Walk on the treadmill for a minimum of 20 seconds to ensure there is enough quality footage to edit.
6) Stop the camera's recording.
7) Repeat steps 3-6 with each pair of varying shank boots at both 0% grade and 15% grade.
8) Upload all the videos to Lightworks. Within the software, drag each file to the editing script. Since the clips in this study were shot at 240 frames per second, slowing them down to 30 frames per second requires playing them at 16.67% speed on Lightworks. To slow down each video, right-click on the clip, click 'speed', click 'adjust by percent speed', type '16.67', click accept.
9) Each clip now needs to be analyzed. While the right foot lands on the treadmill, and the left foot is

about to lift off from the treadmill, pause the video (Figure 11). With the video paused, capture a screenshot of the frame. Crop the screenshot like the image provided in Figure 11.

Figure 11: The subject's right foot is in its power stroke, and the left foot is about to lift off the treadmill. Note the right ankle is in a pronation position in this video frame.

10) Using the screen capture from step 9 and a downloaded protractor, open Microsoft PowerPoint to analyze the angle of pronation or supination (Figure 12).

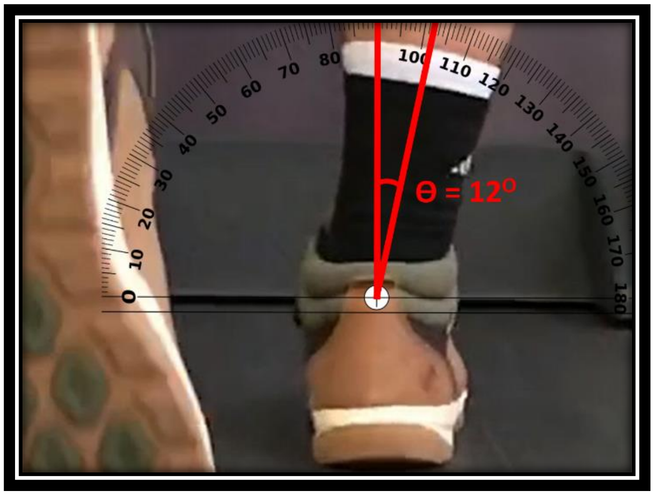

Figure 12: The screen capture of a nylon boot is shown to have a 12^O pronation. This will be compared to other sneakerboots in the discussion of results portion of this report.

11) Repeat steps 9 and 10 for all sneakerboots.

Procedure 4b: Measuring the Angle of Flexure of a Subject's MTP Joint

Similar to the analysis of the pronation of the subject's ankles, this procedure requires a treadmill capable of inclining to 15 % grade. This procedure also requires a video camera capable of shooting a minimum of 120 frames per second. A free video editing software (Lightworks) was used in this study to analyze results.

1) Position the camera on the left side of the treadmill. Be sure to have the lift-off of each sneakerboot in the frame of the camera. The goal is to measure the angle at which the MTP joint flexes.
2) Start the treadmill at 3.5 miles per hour and zero percent grade.
3) With the treadmill running, position a makeshift clapperboard with the label of the test about to be conducted on it (write "12 Ply TPCF 15% Grade" for example). This practice will make editing the video much easier when the thumbnail of each video is what test was conducted.
4) Begin recording on the camera.
5) Walk on the treadmill for a minimum of 20 seconds to ensure there is enough quality footage to edit.
6) Repeat steps 3-6 with each pair of varying shank boots at both 0% grade and 15% grade.
7) Upload all the videos to Lightworks. Within the software, drag each file to the editing script. Since the clips in this study were shot at 240 frames per second, slowing them down to 30 frames per second requires playing them at 16.67% speed on Lightworks. To slow down each video, right-click on the clip, click 'speed', click 'adjust by percent speed', type '16.67', click accept.
8) Each clip now needs to be analyzed. In each clip, when the right foot is applying forward power and is about to lift off, pause the video (Figure 13). With the video paused, capture a screenshot of the frame using the windows snipping tool.

Figure 13: This frame indicates when the optimal time to pause the clip and capture the screenshot is.

9) Using the screenshot from step 9, and a downloaded protractor, it is now possible to measure the angle of flexure of the MTP joint (Figure 14).

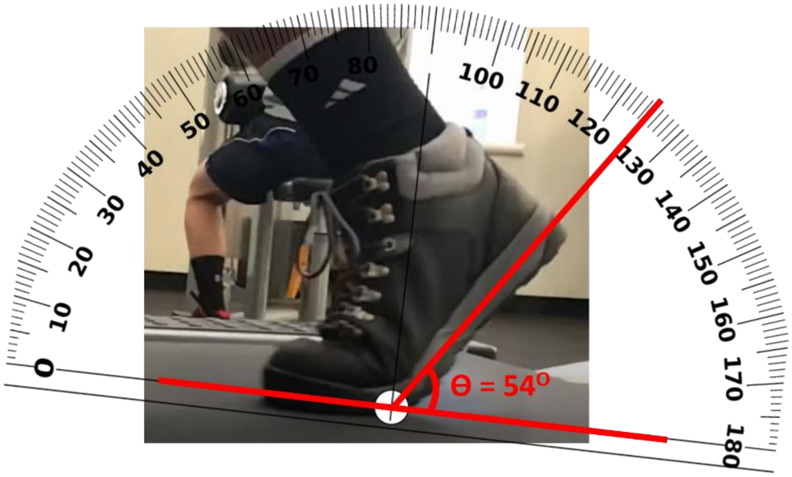

Figure 14: The MTP joint flexion was measured as 54^{O} *for the sneakerboot pictured above. For a comprehensive comparison of all sneakerboots, refer to the discussion of results section of this report.*

10) Repeat steps 9 and 10 for all sneakerboots.

Theory and Analysis:

Two theories were tested in this study: (A) does a stiffer shank in a sneakerboot translates into more efficient aerobic performance of the wearer, and (B) does a stiffer shank alter the walking gait of the wearer? These theories were tested by measuring the heart rate, foot pronation, and foot flexure of a

21-year-old male subject with a size 10.5 (USA) foot. Along with the quantitative findings of this study, qualitative research was also conducted during a two-month sneakerboot cycling schedule. This qualitative investigation was used to gauge the overall comfort of each boot and to provide testimonial legitimacy to the quantitative findings.

The theory that stiffer shanks improve aerobic efficiency was tested by measuring the heart rate of the wearer at two different levels – 0% grade and 15% grade. Heart rate is closely related to the oxygen consumption of an individual, and therefore inferred from heart rate data. The timeframe of this study prevented researchers from measuring the individual's respiratory cycles. The test subject walked each grade with each material twice (Procedure 3). Both raw and plotted data from these tests are provided in the Discussion of Results portion of this paper.

Human gait also plays a role in the aerobic efficiency of a hiker. Measuring the angle of flexure of the hiking boot via slow motion video provides information about how the MTP joint bends with each of the sneakerboots. Measuring the pronation and supination of the test subject's ankle relates to the possibility of rolling/ spraining an ankle during hikes. Measuring the walking gait of the subject was achieved by recording the test subject on a treadmill with each boot at each percent grade (both from a side view and a rear view).

Discussion of Results:

Based on the properties shown in Table 1, it is expected for the carbon fiber shanks to be much stiffer than both the flax and nylon shanks. This is supported by the empirical results displayed in Figure 15. The longitudinal stiffness of each shank was calculated using Procedure 2: Testing Longitudinal Stiffness of Shanks. The PEEK impregnated carbon fiber shanks are an order of magnitude stiffer than both the flax and nylon shanks. The data from which this data was collected is available in Appendix 2.

Carbon fiber is known for its high stiffness, but a lesser known property is its brittleness. Unlike the flax and nylon shanks, the carbon fiber specimens are more prone to fracture when experiencing large deformations. This was apparent during the two-month comfort testing of the sneakerboots. While wearing the 9 Ply TPCF sneakerboots, the researcher (and author of this report) snapped a shank while climbing a stone staircase. An audible snap followed by cracking sounds from the right boot were heard after applying full body weight to the middle of the boot on the edge of the stair. The cause for this failure could be due to a debonding of several plies from each other or because of the cracking of the PEEK matrix material.

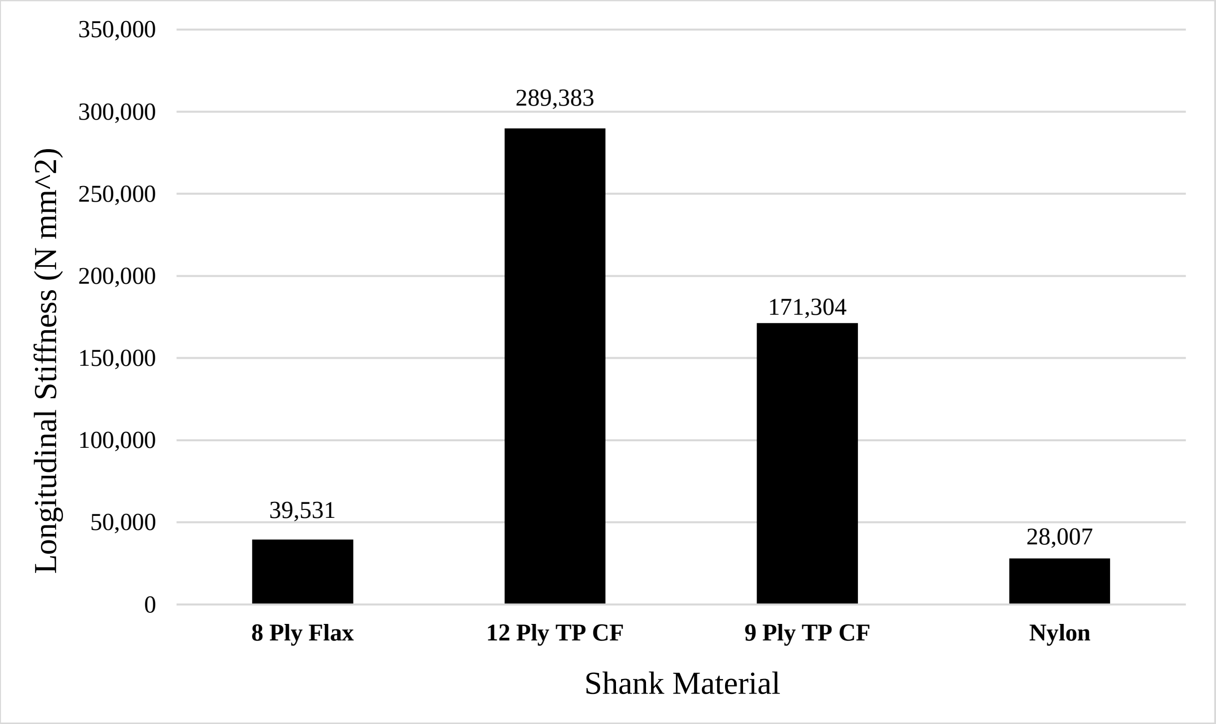

Figure 15: The data from the graph above was generated using Procedure 2: Testing Longitudinal Stiffness of Shanks.

The heart rate testing also yielded tests in line with the theory that stiffer shanks will improve the aerobic performance of the test subject (Figure 16, Figure 17). While the test conditions were maintained as consistent as possible, it is important to note the overwhelming number of variables that contribute to human heart rate: diet, amount of sleep, time of day, temperature, barometric pressure, previous activity in the day, and caffeine consumption. Tests were conducted after 9:00 pm – roughly two hours after the test subject's dinner. Caffeine consumption was kept constant with a cup at 10:00 am and 2:00 pm daily. The climate in the College Park Hall gym is temperature controlled to 66 °F. The same Life Fitness HDTV model treadmill was used to record all heart rates in this study to ensure consistent use of machinery. The test subject maintained a sleep schedule from 2:00 am – 10:00 am.

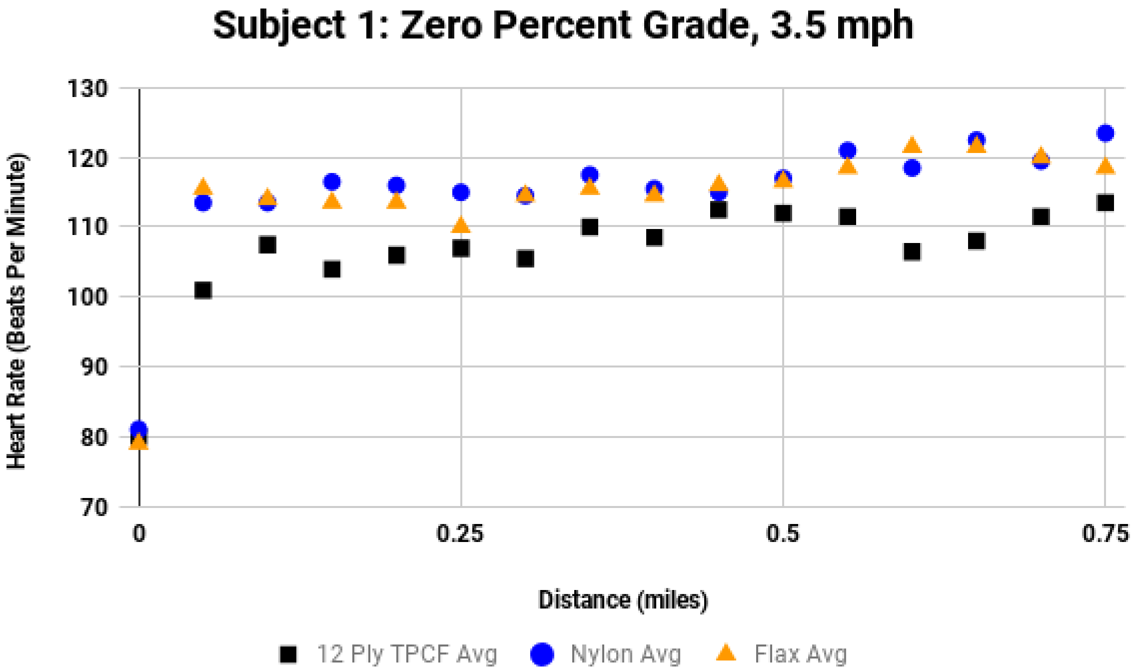

Figure 16: The Plot above relates the heart rate of the test subject (bpm) to the distance walked. The average heart rates are measured from two identical tests. As the plot above indicates, the stiffer carbon fiber sneakerboots result in a lower heart rate over the duration of the test. This suggests that less energy is consumed by the hiker while wearing sneakerboots with carbon fiber shanks.

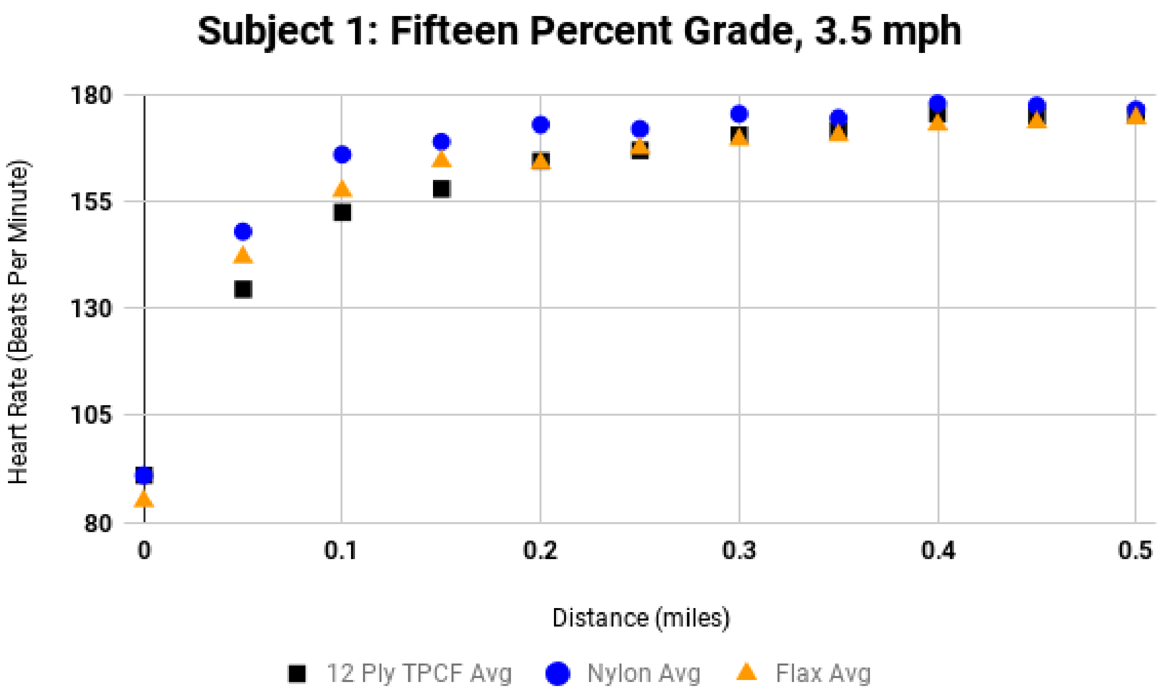

Figure 17: The average heart rate of the subject wearing each boot is plotted above. The averages are based on two identical trials, recorded on separate days. While the boots all plateau to a heart rate of roughly 180 beats per minute, the carbon fiber shanks extend the period of time to reach 180 bpm. This extended heart rate ramping time means less energy is consumed in the first half of the test, therefore the onset of fatigue will occur later in the hike.

As the graphs of heart rate versus distance walked indicate, the average heart rate of the subject at each distance is generally the lowest for the carbon fiber shanks. This is most apparent in the zero percent grade test. It was thought that the stiffer carbon fiber shanks would play a more prominent role in the heart rate during the more strenuous 15% grade test, but the 0% tests indicate a larger difference between the materials. It is important to note that in the 15% grade test, all materials eventually lead to a plateau of nearly 180 beats per minute. The difference between the materials in Figure 17 is their contribution to the ramping of heart rate. The boots with carbon fiber shanks ramp slower than the boots with flax, while the flax ramps slower than the nylon shanks. While this ramping in the 15% grade test is only present for 0.3 miles before the plateauing heart rate, the test subject expended less energy in this time.

Unlike the consistent ramping of heart rate in Figure 17, Figure 16 shows more fluctuation. For all materials in Figure 16, the data trends upward with a positive slope, but the heart rate jumps both up and down throughout the test. This could be a result of the less strenuous nature of the test – the leg muscles require less oxygen to be pumped to them throughout the duration of the test. Perhaps the underlying variables that contribute to heart rate are more distinguishable in the 0% test, while the dominant variable in the 15% test is the exercise itself.

Another anomaly seen in the 0% grade test is the lack of plateauing heart rate. While the 15% grade test induced a plateaued heart rate of 90% that of the maximum heart rate for the test subject (220 minus an age of 21 equaling 199 beats per minute), the 0% test did not show a plateau for any of the materials. To rectify this anomaly future tests should increase the length of the 0% grade test from 0.75 miles to 1.5 miles. This increase in distance could potentially increase the chances of attaining the desired plateaued heart rate such that a comparison of ramping time can be made.

The slow-motion videos of the boots (described in Procedures 4a and 4b) were analyzed for each of the materials. The results of Procedure 4b: Measuring Angle of Flexure of Subject’s MTP Joint were performed to provide insight toward the heart rate results shown in Figures 16 and 17. These angle measurement tests also provide insight into the comfort tests that were qualitatively conducted over a two-month period. The results of procedure 4b are shown in Figure 18 below.

Nylon 0% - 47°

Nylon 15% - 49°

Flax 0% - 51°

8 Ply Flax 15% - 60°

9 Ply TPCF 0% - 41°

9 Ply TPCF 15% - 55°

12 Ply TPCF 0% - 54°

12 Ply TPCF 15% - 50°

Figure 18: Each material, percent grade of the treadmill, and angle of dorsiflexion are provided. While the nylon test proved to have the boot slightly out of frame during the crucial moment of the boot flexing, an angle measurement was still able to be calculated. It is also important to note the fact that the iPhone 7+ captured a better focus on certain tests over others.

No distinct relationship can be tied between the stiffness of the shanks and the dorsiflexion angle of the MTP joint. While there is no distinct relationship between the stiffness of the shanks and the angle of flexure – there is a minor difference in feel between the boots. This difference in comfort is most notable when climbing stairs in a similar fashion to which the 9 ply TPCF shank broke. Boots with the stiffer shanks do not deform as easily, making for a more comfortable walking experience. The carbon fiber shanks also provide more protection to the foot when stepping on an object such as a tree root – the foot does not bend as readily and therefor is more comfortable to the wearer.

Another minorly noticeable comfort difference between the carbon fiber shanks versus flax and nylon samples is the carbon fiber's springiness. This was seen both in the longitudinal stiffness tests (prior to the shanks installation) and in real world usage. When the shanks were deformed in the cantilever testing of ISO 18896, the nylon specimen continued to droop even after the 500-gram and 1,000-gram masses were removed. The flax shanks showed less drooping, while the carbon fiber shanks returned very quickly (like a spring) to their original position. This is consistent with the “tree root” tests in real world usage. When the foot traverses a tree root, the boots with carbon fiber shanks deform, but spring back to their original positions when the foot begins to lift off the root. The nylon and flax shanks seemed less “lively” in a scenario like this and were subsequently considered less comfortable.

Like the dorsiflexion testing, there is no distinguishable relationship between the stiffness of the shank and the degree of pronation the subject has in their gait (Figure 19). It is apparent, though, that the amount of pronation in the ankle for each material was exacerbated by the raising of the treadmill grade.

Nylon 0% - 7° | Nylon 15% - 12° | 8 Ply Flax 0% - 4.5° | 8 Ply Flax 15% - 5°

9 Ply TPCF 0% - 6° | 9 Ply TPCF 15% - 7° | 12 Ply TPCF 0% - 12° | 12 Ply TPCF 15% - 12°

Figure 19: Screenshots of each material at both 0% and 15% treadmill grades are provided. This figure indicates that increases in the treadmill incline increase the degree of pronation for the test subject.

While the shank *material* in this research endeavor show a minimal difference in pronation – the incline of the treadmill seems to increase the amount of ankle pronation for the subject. A possible reason for this is the additional strain the leg muscles undergo during an inclined test – this additional strain compromises the walking form of the test subject. Pronation is becoming a more recognizable cause for leg joint pain as well as lower back pain. This topic could have an entire research study devoted to it. Possible approaches to further investigate this topic in the future are to both increase the number of test subjects in the study, take more data samples, increase the number of treadmill grades analyzed, and use dedicated shoe inserts to measure their effect on pronation.

Synthesis/ Conclusions and Recommendations:

The purpose of this research endeavor is to identify and record the differences in human performance from altering the shank material of a Forsake "Trail" sneakerboot. Three materials were analyzed in this study: the legacy nylon material that is currently used in Forsake boots, a PEEK thermoplastic impregnated carbon fiber, and a resin impregnated flax composite. The stiffness of each material was calculated using a standardized ISO 18896 longitudinal stiffness test. Each shank was then installed in size 10.5 (USA) "Trail" boots using an identical installation method in Forsake's factory. The human performance tests were quantified by measuring the heart rate of a 195-pound male test subject wearing boots of varying shank material. The heart rate of the subject was measured two times for each combination of shank material and treadmill incline. The walking gait of the subject was also analyzed using the 240 frames per second slow-motion video capabilities of an iPhone 7+ smartphone and an iPad Pro 9.7" tablet.

The results of ISO test 18896 were striking – the carbon fiber shanks were an order of magnitude stiffer than the nylon and flax shanks. The 12 ply carbon fiber shanks have a longitudinal stiffness of 289,383 N-mm^2, the 9 ply carbon fiber shanks (that were not considered after the shank in the right boot broke) are 171,304 N-mm^2, the flax shanks are 39,513 N-mm^2, and the nylon shanks are 28,007 N-mm^2. These differences in stiffness were expected to play a larger role in performance than were found through the empirical testing. Using Procedure 3 it was found that there was an improvement in aerobic performance of the test subject while wearing the boots with carbon fiber shanks embedded in them. In the 0.75-mile, 0% grade test, the carbon fiber shanks reduced the heart rate of the wearer across the entire 0.75 miles compared with the flax and nylon boots. In the 0.5-mile, 15% grade test, the carbon fiber shanks lengthened the ramping up of heart rate for the wearer; the slope leading to the 180 beats per minute plateau was more gradual compared to that of nylon and flax. The shank material used in each boot had no effect on the walking gait of the wearer. Aspects of the walking gait analyzed were both the dorsiflexion of the foot and the pronation of the ankle. In both metrics, the treadmill's incline had a greater effect on the walking gait than the material of the shank embedded in the boot.

The data collected in this study would be more significant if a larger sample size was used in tests. Having more test subjects, more boots, more materials of shank, more treadmill grades and more trials of each combination would produce more significant results and researchers would be able to identify outliers in the data. This research endeavor attempted to touch on each of the topics rather than diving deeper into a single one of them. It would also be interesting to investigate further methods of fabricating BMC shanks from thermoplastic impregnated carbon fibers.

It is the recommendation of the author of this report to continue fabricating Forsake sneakerboots with the legacy nylon material until larger, more reliable data sets are collected. If a composite manufacturing company with a sizable waste stream is willing to donate or reduce the cost of their carbon fiber scraps, this outlet can be pursued to attain a marketing advantage over competitors. Deciding to use carbon fiber shanks in future products will require a mass production strategy for them – something that cannot be overlooked. Having high end materials such as carbon fiber can increase the cost to manufacture the product, but these materials can also increase the asking price of the product.

Another alternative to using stiff, carbon fiber shanks is to redesign the existing nylon shanks to increase their rigidity through geometric changes. While it is impractical to design shanks as an I-beam, these rigid beams can be used as inspiration. Increasing the rigidity of the nylon shank will give the sneakerboot some of the carbon fiber's characteristics but not all. One characteristic of the carbon fiber shanks that would be impossible to recreate with nylon is its springiness. This springiness of the carbon fiber increased the wearer comfort when traversing geometries such as tree roots; the carbon fiber deformed when the foot applied pressure to the tree root and snapped back (like a spring) into its original shape when lifting the foot up.

As a final recommendation to Forsake, it is important to continue to pursuing options that are not the norm for the industry. As the name of the company indicates – Forsake should continue to bypass the beaten path and look for opportunities to innovate. While this concept for a high-performance shank does not currently have a strong backing of data, research projects like this one can be further pursued to whether a future design alteration should be made.

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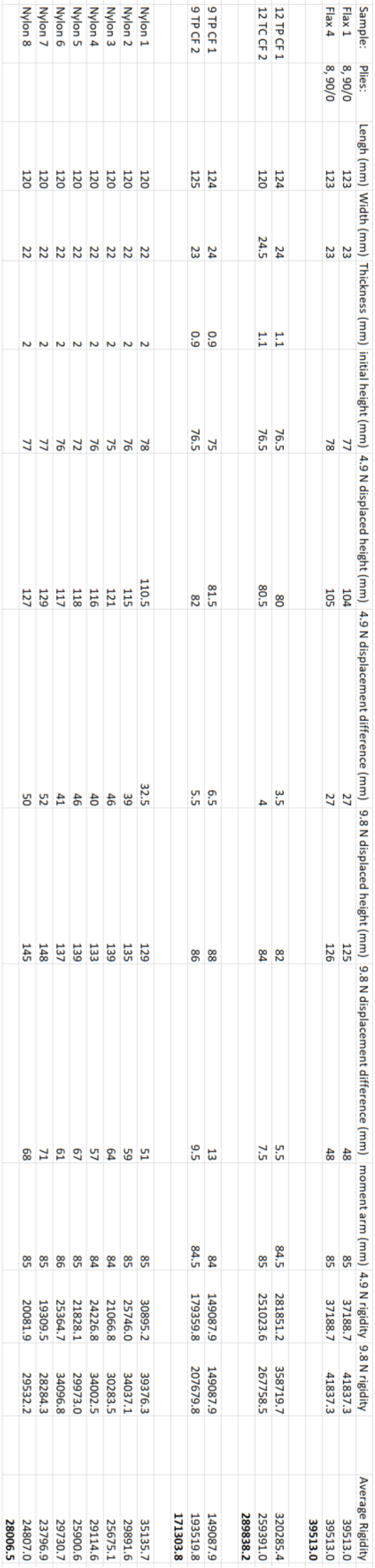
Appendix 1: Types of Shanks Found in Name Brand Shoes and Boots

Brand	**Material(s)**
Alden	Metal
Allen Edmonds	No shank
Bass	Nylon and Steel
Caterpillar	Steel, no shank
Chippewa	Steel and Fiberglass
Church's	Metal
Clarks	Metal, Plastic or no Shank
Crocket and Jones	Wood
Diemme	No shank
Dr. Martens	No shank
Eastland	Steel, no shank
Ecco	Metal, Carbon Fiber
Frye	Steel and Fiberglass
Johnston and Murphy	Fiberglass
Leon Leonwood Bean	Steel
Loake	Metal Flute with board shank and a wooden shank
Meermin	Steel
New England Outerwear	No shank
Paul Smith	Metal
Red Wing	Steel and combo of Nylon, Plastic and Fiberglass
RM Williams	Fiberglass
Russel Moccasin	Steel
Sorel	Fiberglass, Nylon and no shank
Steve Madden	Did not understand question
Timberland	Metal or Fiberglass (interchangably) and Nylon
Tricker's	Wood
Viberg	Steel or Wood
Walkover	Metal
Wolverine	Nylon and Fiberglass
Yuketen	Steel
Forsake	**Nylon**

Appendix 2: Longitudinal Stiffness Raw Data



Sample:	Plies:	Lengh (mm)	Width (mm)	Thickness (mm)	initial height (mm)	4.9 N displaced height (mm)	4.9 N displacement difference (mm)	9.8 N displaced height (mm)	9.8 N displacement difference (mm)	moment arm (mm)	4.9 N rigidity	9.8 N rigidity		Average Rigidity
Flax 1	8, 90/0	123	23		77	104	27	125	48	85	37188.7	41837.3		39513.0
Flax 4	8, 90/0	123	23		78	105	27	126	48	85	37188.7	41837.3		39513.0
														39513.0
12 TP CF 1		124	24	1.1	76.5	80	3.5	82	5.5	84.5	281851.2	358719.7		320285.4
12 TC CF 2		120	24.5	1.1	76.5	80.5	4	84	7.5	85	251023.6	267758.5		259391.0
														289838.2
9 TP CF 1		124	24	0.9	75	81.5	6.5	88	13	84	149087.9	149087.9		149087.9
9 TP CF 2		125	23	0.9	76.5	82	5.5	86	9.5	84.5	179359.8	207679.8		193519.8
														171303.8
Nylon 1		120	22	2	78	110.5	32.5	129	51	85	30895.2	39376.3		35135.7
Nylon 2		120	22	2	76	115	39	135	59	85	25746.0	34037.1		29891.6
Nylon 3		120	22	2	75	121	46	139	64	84	21066.8	30283.5		25675.1
Nylon 4		120	22	2	76	116	40	133	57	84	24226.8	34002.5		29114.6
Nylon 5		120	22	2	72	118	46	139	67	85	21828.1	29973.0		25900.6
Nylon 6		120	22	2	76	117	41	137	61	86	25364.7	34096.8		29730.7
Nylon 7		120	22	2	77	129	52	148	71	85	19309.5	28284.3		23796.9
Nylon 8		120	22	2	77	127	50	145	68	85	20081.9	29532.2		24807.0
														28006.5