An Innovative Manufacturing Technique Which Integrates Multi-Axial Shear Stress Sensors in Footwear for Female Distance Runners to Examine the Foot-Shoe Interface

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SPD 688: Thesis Proof of Concept Studio

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SECTION #1: FALL TERM

Introduction

Technology is the future. Most people carry mini-computers known as cell phones in their pockets, have technologically-advanced fitness trackers on their wrists, and might even have self-lacing shoes. Data-driven design, artificial intelligence, and machine learning allow companies to reimagine how products function for athletes and how design is executed.

If technology is the future, why are athlete's footwear options not more advanced? Despite the rise of smart footwear and the use of technology to measure athletes' biomechanics and kinematics, there are currently no out-of-laboratory solutions for measuring shear between an athlete's foot and their shoe or between an athlete's shoe and the contact surface. Today, shear forces are measured by force plates mounted to the floor within motion analysis laboratories (Landsman, 2012). These plates measure both vertical and horizontal forces by shifting an imperceptible amount when contacted. This measurement technique is expensive and often limits the data collected to only a stride length. The capability to measure shear stress in an out-of-laboratory would have major implications for rehabilitation and injury prevention, developing an out-of-laboratory kinematic reconstruction when used in combination with existing sensor technologies, measuring residual limb tissue health, and determining prosthetic socket fit.

This paper explores how an innovative method of manufacturing performance training footwear for female distance runners was engineered in a way that allows for the integration of an optoelectronics-based, multi-axial shear sensor to analyze the foot-shoe interface.

Professional Interest

I am energized by solving complex problems and believe that great design can always be improved. I believe that sports products should be advanced through the integration of technology and data-driven design to deliver performance solutions to all athletes. My work improves existing designs by solving complex problems and investigating the intersection of technology, engineering, and design. This project will be an innovative, beautiful, and highly functional footwear solution that incorporates a multi-axial shear sensor to promote running performance and advance the field of biomechanics and human performance analysis.

I believe that this project will attract future employers and provide me with valuable experience creating innovative products. Not only will I understand how to design functional running footwear, but I will understand how to integrate technology into product. Additionally, it will be valuable to work with a team of experts as almost every career will depend on teamwork.

Personal Strengths

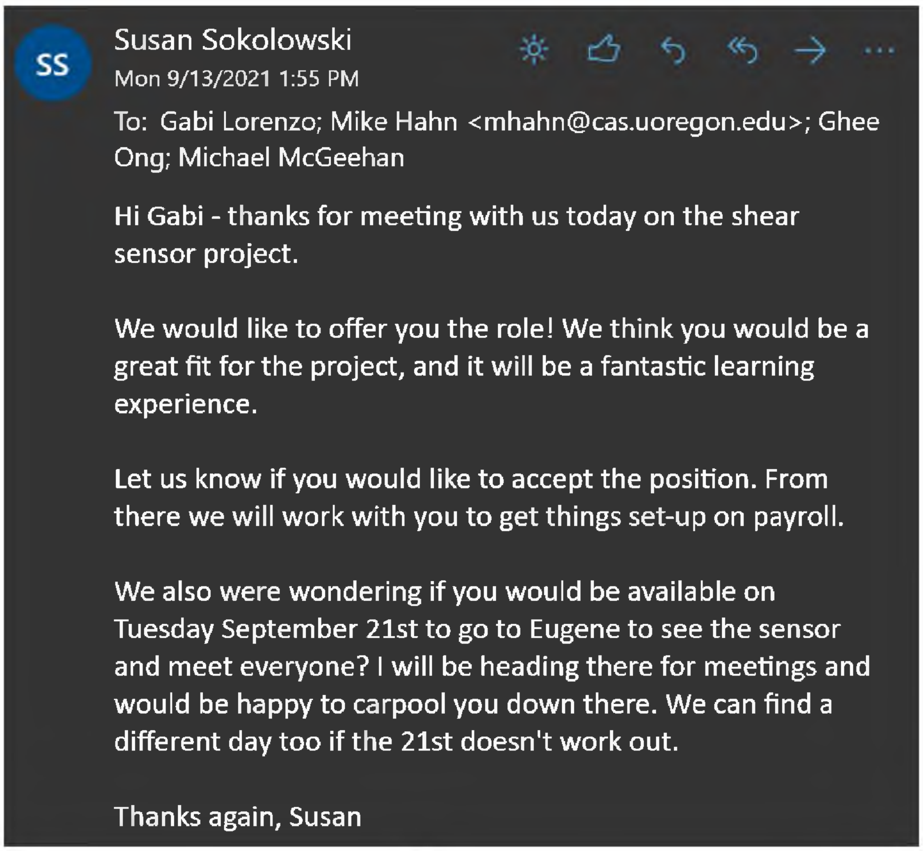
Everyone has key strengths which help them accomplish their goals. According to the StrengthsFinder test, my top five strengths are belief, strategic, discipline, achiever, and connectedness. These strengths will be part of the reason I produce a successful capstone thesis project. My "belief" will keep me passionate and motivated because I know that what I'm doing is meaningful. My "strategic" nature will help me plan for the unexpected, identify possible obstacles that might block my completion, and help me make decisions that will ensure the success of my project. My "discipline" and "achiever" strengths will help me efficiently accomplish tasks and continue with strong work ethic until the project is finished. Finally, my "connectedness" strength will help me show others how important this project is and convince them of its intent and purpose.

Mentors

A team of experts from the Eugene Campus developed the shear sensor technology and will be mentors for this project. The team consists of Dr. Mike Hahn, Dr. Keat Ghee Ong, and Dr. Michael McGeehan. Dr. Susan Sokolowski will act as a faculty advisor throughout the duration of the project.

Dr. Mike Hahn serves as the Director of the Bowerman Sports Science Clinic and as an Associate Professor of Human Physiology. Dr. Keat Ghee Ong is a Professor at the Phil & Penny Knight Campus, and he has expertise in physics, electrical engineering, biochemistry, and chemistry. Dr. Michael McGeehan is a Postdoctoral Researcher at the Phil & Penny Knight Campus, and he focuses on the development of embedded electronics and sensors for sport applications. Dr. Susan Sokolowski is the founding director and an associate professor of the Sports Product Design Graduate Program, and she has 25+ years of performance footwear design experience.

Weekly meetings will occur with my faculty advisor, Dr. Sokolowski. Monthly meetings will occur with the team from the Eugene Campus. These meetings will be used to develop concepts, share research knowledge, evaluate prototypes, and validate ideas.


SS
Susan Sokolowski
Mon 9/13/2021 1:55 PM
To: Gabi Lorenzo; Mike Hahn <mhahn@cas.uoregon.edu>; Ghee Ong; Michael McGeehan

Hi Gabi - thanks for meeting with us today on the shear sensor project.

We would like to offer you the role! We think you would be a great fit for the project, and it will be a fantastic learning experience.

Let us know if you would like to accept the position. From there we will work with you to get things set-up on payroll.

We also were wondering if you would be available on Tuesday September 21st to go to Eugene to see the sensor and meet everyone? I will be heading there for meetings and would be happy to carpool you down there. We can find a different day too if the 21st doesn't work out.

Thanks again, Susan

Figure 1. Email confirmation of involvement in the project from the Eugene Campus team & faculty advisor.

At the end of winter term, I also secured Kiersten Muenchinger (Product Design faculty member at University of Oregon) and Evan Day (Research Scientist at Brooks Running) as additional mentors.

Why Use a Shear Sensor to Examine the Foot-Shoe Interface?

Footwear with an integrated optoelectronics-based, multi-axial shear sensor would allow the foot-shoe interfaced to be analyzed. Examining the shear stress that occurs at the foot-shoe interface is extremely difficult and something that has not been done before. Data collected from the analysis of the shear stress at the foot-shoe interface could provide opportunities to improve performance efficiencies and athlete biomechanics. The ability to measure shear at this interface has major implications for investigating the foot's tissue health as well as determining proper shoe fit. Additionally, measuring the shear between the athlete and the environment has the potential to pave the way for calculating the inverse dynamics of the athlete and developing a complete kinetic model by first utilizing Inertial Measurement Units (IMUs) to determine the kinematics of the athlete. Finally, if multiple sensors can be integrated into the footwear, this would allow for precise shear analysis at different points of the foot, such as the first metatarsal head, fifth metatarsal head, and calcaneus. This precise analysis is not possible using force plates which is the current standard method for measuring shear stress in a laboratory setting (M. McGeehan, personal communication, October 22, 2021).

History of Running & Running Footwear Technology

While it is difficult to determine the exact origin of running, this research will investigate the beginning of running as a sport and the use of technology to advance running performance. It is widely accepted that the ancient Olympic Games commenced in 776 B.C. with a 600-foot stadium race (*The History Cf Track And Field. Where Running Started.*, n.d.). Before the Olympics were the Tailteann Games, a festival held by the Irish which included several competitive events. The earliest record of the Tailteann Games is 1829 B.C. in Ireland. These games included everything from running, high jump, long jump, and spear throwing to sword fighting, boxing, archery, and chariot racing (Kercher, 2021).

In the United States, track and field athletics were established in the 1860s. The first collegiate race was held in 1873 by the Intercollegiate Association of Amateur Athletes of America, the nation's first national athletic ground. In 1921, the first NCAA national championships were held for men. Women were included in the Olympic Games' track and field events in 1928. However, women's track was not widely accepted until the 1970s when the sport saw a rise in popularity.

The "Running Boom of the '70s" was spurred on by a number of events. Bill Bowerman published his book, *Jogging,* in 1967 after observing New Zealand's cross-country teams. This book sparked many people to pick up jogging and running. Additionally, Frank Shorter, an American, won the summer Olympics in 1972 which was the impetus many people in the United States needed to start taking running seriously ("The History of Running," 2019). Celebrity runners, including Steve Prefontaine, also boosted the appeal of running (Kercher, 2021).

After the "Running Boom," sports companies began pursuing the use of technology to advance human performance and sports products. Some ways technology has been employed in sports has been wearables (Li et al., 2016), such as pedometers, accelerometers, GPS devices, and heart rate monitors, automatic timing systems, and product manufacturing technologies such as 3D printing or 3D knitting.

Today, wearables are common products for a consumer to own. Measuring number of steps, cadence, distance, location, heart rate, and blood pressure can all be found in a sports watch or fitness tracker. Additionally, there are various insole technologies that can measure plantar pressure. However, there are no options for sensors that can measure shear outside of a laboratory setting.

Figure 2. Brief overview of the history of running.

Athlete Profile

The target athletes for the proposed product are female, 18 to 30 years old, and distance runners. The product will be geared towards heel striking athletes with a normal gait who are interested in analyzing their performance and are early adopters of technology. Heel strikers contact the ground with their heel before other parts of the foot during the running gait cycle. Due to this foot strike, there is decreased ankle motion with increased hip and knee motion. Additionally, this foot strike is more energy efficient than the forefoot strike at moderate to slow speeds.

The target athletes run 30 to 120 miles per week on the road or trail. The athletes exhibit resilience, motivation, and have high endurance levels. Due to the need to maintain their pace for long periods of time, these athletes require footwear designed for comfort, impact attenuation, durability, and thermoregulation.

Additionally, there are many other users who could benefit from an integrated shear sensor in footwear. This work is relevant to human performance specialists and biomechanists as the development of an out-of-laboratory, complete kinetic model would be revolutionary for analyzing athlete movements. Another group of people who would be interested in leveraging this product would be coaches. Coaches would be interested in evaluating the shear stress their athletes are enduring and noting how different gaits or training exercises might affect this shear stress. Further, the ability to measure shear stress within footwear would be a valuable tool for sports product developers and designers to validate their future footwear projects. For example, if the team behind Zion Williamsons' shoe blowout had been able to test the amount of shear stress someone of his size would place on the shoe, then the blowout may have been avoidable through the recommendation that Williamson wear a more robust shoe.

Figure 3. Zion Williamson's shoe blowout (Newcomb, 2019).

The technology employed within this footwear could be applied to other sports and would be especially relevant to sports involving cutting movements such as soccer, tennis, and basketball. Additional applications of the shear sensor would greatly expand the target athlete profile.

Jobs to Be Done

The created footwear needs to function as well or better than existing road and trail running training shoes, and it must have a functioning sensor. The shoe needs thoughtful cushioning and impact attenuation to keep the runner injury free and comfortable during long runs. The shoe needs to be made from durable materials so the runner can wear it for as many miles as possible. Additionally, the sensor setup and entire footwear system needs to be simple and intuitive to use.

Jobs to be done of the individual components of the footwear is included within the Product Anatomy section of the paper.

Target Market

The target market consists of three main segments, athletes/coaches, clinics, and sports product design companies/research biomechanists. The created footwear will target the domestic market.

First, the athlete market will be determined through known number of road racers and percentages based on sex, age, likelihood to adopt technology, and foot strike. Road runners were focused on for this analysis, since it was easily accessible information and many distance runners run on both the road and the trail. In 2018, 18.1 million Americans registered for road races (Galic, 2021). Additionally, it is known that 17.8% of racers are 18 to 29 years old and 50% of these are female (Galic, 2021). Plus, 28% of Americans are early adopters of technology (Kennedy & Funk, n.d.). Finally, 70% of distance runners are heel-strikers (Klein & D.P.T, 2021). The combination of this information leads to the conclusion that there are approximately 31,500 athletes in the target market for this footwear.

Next, the clinical market will be determined based on the domestic market. The clinical market consists of physical therapists, occupational therapists, and university sports science clinics. It is estimated that there are 38,800 physical and occupation therapy clinics in the United States (LaRosa, n.d.). It is known that there are 560 universities across the United States which offer Sports Science degrees and therefore would have a sports science clinic (*560 Institutions Offering Sports Science Courses In the USA*, n.d.). The addition of these two variables yields the conclusion that the clinical market would contain 39,360 clinics. Also, there are over 1,000 sports product design companies which may be interested in this product for research purposes.

While the product will be designed for female distance runners, the target market will be broken into three launches. The first launch, which will be the focus of my thesis, will focus on biomechanists and sports product design companies which are looking to use this product for research. The second launch would focus on elite athletes, coaches, and clinicians. The third launch would focus on athletes who are early adopters of technology and are interested in improving their performance. After these stages roll out, the product line could be expanded.

Sport Environment

The sport environment where the athlete would use the proposed footwear product includes a laboratory, track, road, and trail. Due to this broad environment, both a road and trail shoe will need to be developed. The road shoe will be built for running in the laboratory at Bowerman Sports Science Clinic and around the track at Hayward Field. Both of these are located in Eugene, Oregon. The laboratory is indoors and features a treadmill to run on. This indoor environment would be 68°F with 35-45% humidity (Stuba, 2014). Additionally, the outdoor track environment consists of a rubber track surface and the footwear will be tested during spring. The weather could be dry or raining, and 40-70°F with less than 10% humidity (*Eugene Climate, Weather By Month, Average Temperature (Oregon, United States) - Weather Spark*, n.d.). Any shoe suitable for the outdoor track would also be suitable to run on pavement or asphalt in the Eugene area.

Product Rules

In order to prove that the proposed footwear product is accurate and successful, the entire system will need to be validated. The integration of the shear sensor into footwear will need to be validated within a laboratory environment, on a road or track, and on the trail in order to comply with the proposed sport environment. This validation will be done with the assistance of existing sensors, including but not limited to motion capture technology, force plates, and IMU sensors.

Additionally, there are two American Society for Testing and Materials (ASTM) standards which should be applied to the product. The first is ASTM F2333 which is a test method for traction characteristics of the athletic shoe-sports surface interface. This test measures the effects of athletic shoe outsole design and materials on the shoe-surface interface during linear translational and rotational motions. It provides information on how to compare shoes using characteristics of the surfaces on which the shoes are tested. These characteristics include surface type, material, condition, and temperature. The testing requires the linear or angular velocity of the shoe to be recorded when subjected to specified loads so that baseline values can be determined, and outsole designs can be compared (F08 Committee, n.d.).

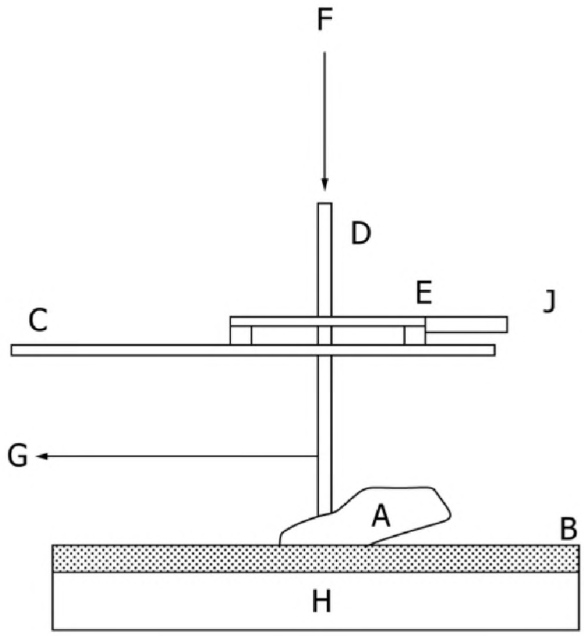


Figure 4. Diagram of a device for measuring linear traction (F08 Committee, n.d., p. 08).

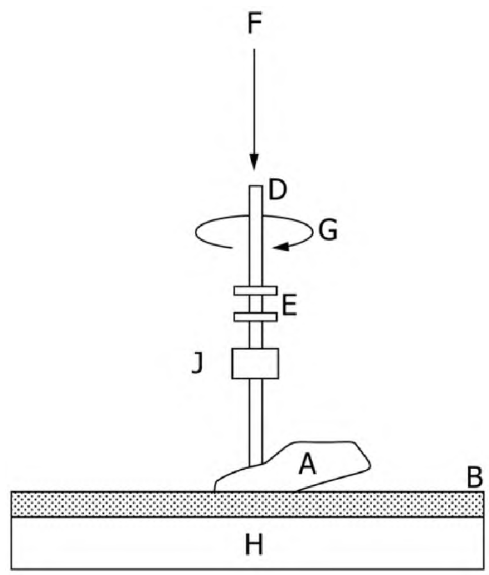


Figure 5. Diagram of a device for measuring rotational traction(F08 Committee, n.d., p. 08).

The second ASTM standard that should be applied is ASTM F3463 which is the Standard Guide for Ensuring the Safety of Connected Consumer Products. This standard defines a connected consumer product as any device that can connect to a network directly or indirectly and is assigned an internet, Bluetooth, or other communication protocol address or identifier. The shear sensor which will be integrated into the proposed footwear product will have a Bluetooth module and therefore will fall into the classification of being a connected consumer product. Additionally, the product defines safety as being freed from an unreasonable risk of physical injury or illness resulting from mechanical contact, hazardous energy release, or exposure to hazardous chemicals from the product. The standards does not include privacy, personal data security, or the safety from physical harm resulting from privacy or personal data breaches (*Subcommittee F08.54 : Published Standards under F08.54 Jurisdiction*, n.d.).

Initial Line Plan

The initial line plan for the proposed footwear project includes two trainers, a women's trail shoe and a women's road shoe. The women's shoes will be built around a last specifically designed based on the female foot morphology. Both the trail and road versions of the trainer will feature similar midsoles. The outsoles and uppers will have variations to fit the specific environments they are created for.

All shoes in the line will feature aesthetic styles and colorways that highlight the unique models of the trainer while keeping the collection recognizably similar. Every model needs to be capable of measuring multi-axial shear stress and record the data via Bluetooth to allow athletes to analyze the lateral force components on their feet. Additionally, the shoes need to be designed with a breathable upper for all day comfort, ultra-lightweight cushioning with high energy return, and innovative traction for a confident grip on the ground.

State-of-the-Art Sensor Technology

As technology becomes more advanced, wearable performance devices and sensors become more accessible to elite athletes and the general population. Wearables allow athletes to "monitor functional movements, workloads, and biometric markets to maximize performance and minimize injury" (Li et al., 2016). Wearable sensors may measure movement, for example pedometers, accelerometers, and global positioning satellite (GPS) devices, or they may measure physiological metrics, for example heart rate monitors, sleep monitors, and temperatures sensors (Li et al., 2016). Of these types of wearable sensors, many have been adapted to interface with footwear. This section of the paper will examine six of these sensors whose function, design, or integration into product may provide valuable insight into the proposed footwear product line that this paper outlines.

The first noteworthy sensor is a plantar pressure measurement insole system called pedar® by novel.de. The insole system is built to slide into the shoe on top of the existing sockliner. It can be tethered via USB cable, function via Bluetooth, or use SD card storage. These various data collection techniques allow data to be collected anywhere and downloaded simultaneously or after the athletic event has been completed. The system features 99 sensors per insole for full-foot coverage. The sensors are flexible and easily conform to the foot's shape. Additionally, the insole can interface with any shoe size and can be useful for all athletes. The price for the sensor system is unlisted ("Pedar- Footwear Pressure Distribution Measurement," n.d.).

The second sensor worth mentioning is the F-Scan system by Tekscan. This sensor measurement system captures temporal parameters, pressure, and force so various aspects can be measured simultaneously. All sensors are high-resolution for accurate data collection, ultra-thin for in-shoe comfort, and durable enough to last multiple trials. Similar to the pedar® system, the F-Scan system is an insole that built to slide into the shoe on top of the existing sockliner. The system allows graphs and pressure profiles to be displayed in real time for immediate processing and analysis. The price for the sensor system is unlisted (*F-Scan System*, n.d.).

The Smart Insoles by ARION is the third sensor system to examine. Another plantar pressure measurement insole, the Smart Insoles contain eight pressure-sensitive sensors to measure every interaction between the foot and the ground in detail. A durable microfiber cover material is utilized to increase the lifespan of the system. The system is ultra-thin, lightweight, and flexible for minimal affect on athlete performance. Plus, the system has

Bluetooth connectivity for wireless data collection. ARION's Smart Insoles have a retail price of $290 (*ARION | Transform Your Running Technique*, n.d.).

These sensors, the pedar®, F-Scan, and ARION Smart Insoles, all feature a ribbon cable that runs out from the insole. The ribbon cable has a data storage or Bluetooth module attachment at the end which clips onto whatever footwear the athlete is wearing.

Figure 6. State-of-the-art sensor technology for athletic footwear.

Additional sensors that are relevant to research include the ActiSense by IEE, the Torin IQ by Altra, and the Smart Sock by Sensoria. The ActiSense system has eight individual pressure cells that are thin and bendable for limited intrusion. It also includes an IMU sensor for an all-in-one solution. The system allows for data synchronization between the right and left foot devices as well as real-time data display for accurate data analysis and personal data visualization. There is no listed price for this sensor system (*Smart Footwear Sensors - IEE - Smart Sensing Solutions*, n.d.).

The Torin IQ is a running shoe from Altra that includes a plantar pressure measurement system built into the shoe. The measurement system collects data on impact force and location, contact time, and cadence to improve stride and efficiency. Additionally, the sensors interface with an app via Bluetooth and provides on-the-run feedback with live coaching. A replaceable internal battery allows for long-lasting usability. These shoes are the most closely related sensor product to the proposed footwear products this paper outlines, and they retailed for $220. However, these shoes were released for a limited time in 2017, and they are no longer available from Altra (McCoy, 2017). There are two other shoes that have similar sensor systems built into the midsole, Altra's Timp IQ and Under Armour's Record Equipped Speedform Gemini 2. Information on sensor implementation into the shoe and availability to consumers are extremely limited so this paper will not further investigate these sensing footwear options.

The final sensor system that was researched for this paper was the Smart Sock by Sensoria. The sock has three pressure sensors embedded into the washable sock for comfort and flexibility in shoe choice. Additionally, a three-axis accelerometer and altimeter are contained in an ankle device which transmits data via Bluetooth for tracking and analysis from an app. The core ankle device attaches magnetically for ease of use and has USB charging capabilities for quick recharging (*Sensoria Core Pair*, n.d.). The Smart Sock retails for $398.

Figure 7. State-of-the-art sensor technology for athletic footwear, continued.

State-of-the-Art Training Footwear: Trail & Road

There are various high-performing training shoes for both trail and road runners. This section of the paper will outline a few of these to investigate what features and benefits are common to the best-in-class footwear options for distance runners. For the trail running trainers, Saucony's Peregrine 11, HOKA One One's Speedgoat 4, and North Face's Flight VECTIV stood out (Rochfort, 2021; *The Best Trail Runners Cf 2022 + Tips From Tcp Running Coaches*, 2021). For the road running trainers, Saucony's Endorphin Speed 2, HOKA One One's Clifton 8, and Nike's Air Zoom Pegasus 38 are the top contenders for consumers (*Best Long Distance Running Shoes 2021 | Buyer's Guide*, 2021).

Trail Running Trainers

The Peregrine 11 retails for $120. It features Saucony's proprietary PWRRUN cushioning for a fast, responsive ride along with their deep PWRTRAC rubber lugs which provide a versatile grip to tackle any terrain. The shoes are outfitted with a rock plate to protect the foot on rough trails. Additionally, an ultralight, durable top layer adds durability to the comfortable air mesh bootie to create a stellar option for trail runners (*Peregrine 11*, n.d.).

The Speedgoat 4 retails for $145. It employs HOKA's Meta-Rocker geometry to encourage efficient running mechanics. The Vibram Megagrip Hi-Traction outsole features aggressive 5mm lugs for increased traction and flex grooves for freedom of movement. Plus, the toe cap is reinforced for debris protection and abrasion resistance (*HOKA ONE ONE® Speedgoat 4 for Men | HOKA ONE ONE®*, n.d.).

The Flight VECTIV retails for $199. It has a full-length carbon fiber plate for stability. Its rocker technology delivers a smooth ride with enhanced propulsion. The proprietary VECTIV technology is included for maximum energy return on the trail. In addition, the outsole features surface control rubber for improved grip on inclines and declines (*Men's Flight VECTIV™ Trail Shoe | The North Face*, n.d.).

Figure 8. State-of-the-art trail training footwear.

The strengths, weaknesses, areas of opportunities, and threats (SWOT) for each of these products is investigated within the Appendix.

Road Running Trainers

The Endorphin Speed 2 retails for $160. A full-length nylon plate is incorporated into the midsole for a responsive ride. The midsole also has Saucony's proprietary SPEEDROLL shape technology combined with their ultralight PWRRUN PB foam for springiness and high energy return. The outsole is created with abrasion-resistant rubber for increased grip and durability. Saucony also narrowed the heel to lock in the fit (*Men's Endorphin Speed 2 - Running | Saucony*, n.d.).

The Clifton 8 retails for $130. The shoe has an engineered mesh upper for increased breathability and an ultralight midsole foam for the softest feel ever. The extended heel crash pad provides smooth landings and transitions. Plus, the shoe employs HOKA's Meta-Rocker technology for a snappy takeoff (*HOKA ONE ONE® Clifton 8 for Men | HOKA ONE ONE®*, n.d.).

The Air Zoom Pegasus 38 retails for $120. It has mid-level cushioning for tons of energy return and comfort on runs of any length. The mesh upper is engineered for ultimate breathability, and a midfoot webbing is included to keep the foot snug and secure throughout the gait cycle. An Air Zoom unit is located at the forefoot to create a responsive bounce (*Nike Air Zoom Pegasus 38 Men's Road Running Shoes. Nike.Com*, n.d.).

Figure 9. State-of-the-art road training footwear.

The strengths, weaknesses, areas of opportunities, and threats for each of these products is investigated within the Appendix.

Product Anatomy

The proposed footwear products will feature five main components: the upper, sockliner, midsole, outsole, and sensor. The upper is designed to secure, protect, and stabilize the foot. The upper features a heel tab, heel counter, collar, tongue, and strobel. The heel tab allows the shoe to easily be pulled on. The heel counter stabilizes the rearfoot. The collar adds padding to increase comfort at the lockdown point. The tongue allows the upper to move and conform to the foot. The strobel adds stability to the upper and connects the upper and midsole units (Loda, 2018; *The Important Parts of Walking and Running Shoes*, n.d.).

The midsole is built to provide impact attenuation and cushioning. The sockliner sits on top of the midsole, and it increases comfort at the footbed and absorbs moisture. The sensors are typically embedded within the midsole and are designed to introduce technology into the shoe. A rock or energy plate is embedded within the midsole to protect from rocks on rough trails or increase energy return on the road (Loda, 2018; *The Important Parts of Walking and Running Shoes*, n.d.). Some running shoes feature a medial post to control excessive pronation or an additional cushioning unit in the form of an air bag or gel-pack.

The outsole is built as a traction pad to give the athlete a confident grip on target surfaces. It may have a shank to stiffen the shoe and resist torsion (Loda, 2018; *The Important Parts of Walking and Running Shoes*, n.d.).

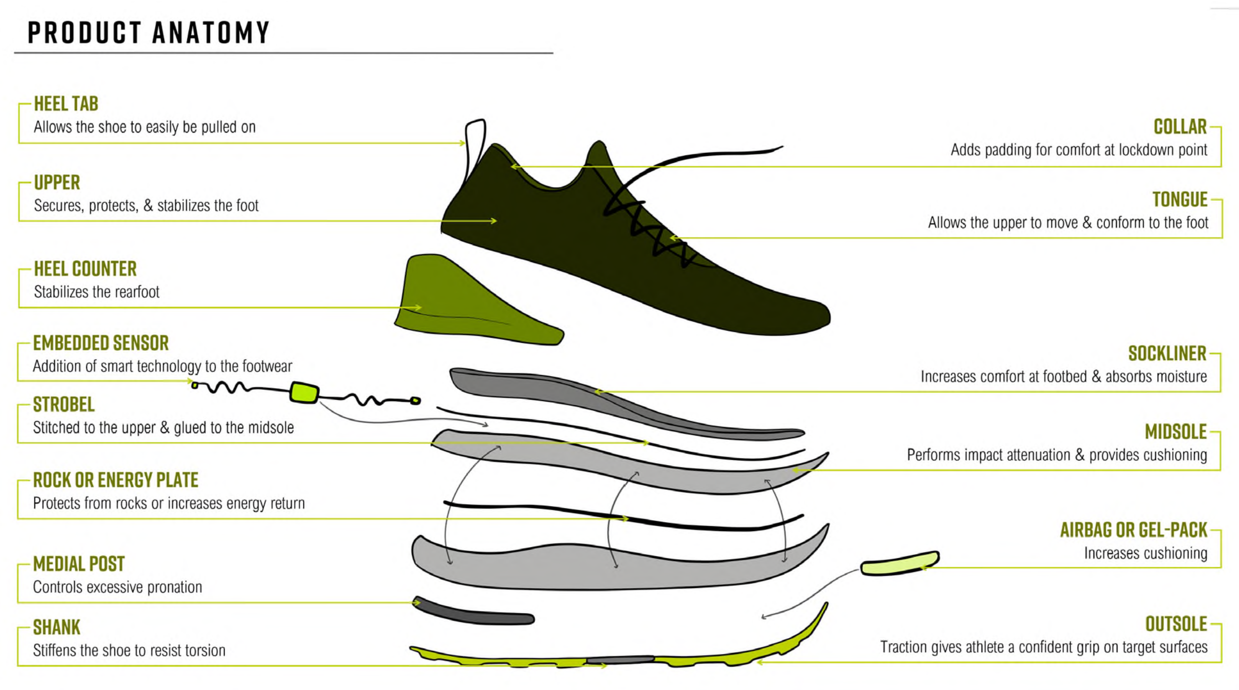


Figure 10. The product anatomy of a smart running shoe.

State-of-the-Art Materials & Manufacturing

This section will overview the best materials and manufacturing techniques used in state-of-the-art running trainers so that this knowledge can be employed within the proposed footwear products. It will not overview the materials and manufacturing of state-of-the-art sensors since the sensor technology is being provided.

The upper is typically a 100% polyester, engineered knit mesh. Alternative upper materials are 100% polyester warp knits, which are frequently combined with heat transfer overlays to provide stability, and synthetic leather. Trail running uppers utilize a Durable Water Repellent (DWR) as well as heat transfer overlays for water proofing. Uppers that are engineered knits created using a flatbed or warp knit knitting machine to knit the upper as one piece (Motawi, 2017). Uppers that are not engineered knits are die-cut and stitched together. Next, details such as overlays and the collar will be heat pressed or flat stitched onto the upper. Overlays are generally a thermoplastic polyurethane (TPU) film or hot melt. The collar is made of open cell, polyurethane (PU) foam which is die-cut. Heels counters are a rigid, TPU that injection molded then glued to the upper (*(5) Materials for Athletic & Sports Shoes Upper, Midsoles and Outsoles | LinkedIn*, n.d.; Motawi, 2016a, 2016b). The strobel is made of non-woven polyester and is stitched to the upper using a strobel machine. The sockliner is placed internally within the upper unit or it may be lightly glued to the top of the strobel. The sockliner is made of ethylene-vinyl acetate (EVA) foam with a woven 100% polyester top cloth with an anti-odor treatment. The sockliner is die-cut then heat pressed into the proper shape (Motawi, 2016a).

The midsole is also EVA foam which is molded using an expansion press, injection molding, or pellet expansion. Then, the midsole is glue to the outsole and upper-strobel unit. Any sensors or plates included within the midsole will need to have cut-outs within the foam so the sensor or plate can be integrated into the midsole, most likely through a gluing process (Motawi, 2018). The plate is typically made of TPU or carbon fiber. The outsole is made of carbon rubber which is hydraulically heat pressed to create the form, and then it is glued to the midsole unit (Motawi, 2016b). The proposed footwear product will not utilize a shank or medial post so the materials & manufacturing of these components will not be investigated.

Intellectual Property Landscape

Relevant intellectual property to this research includes both the intellectual property that currently exists for the shear sensor and patents related to footwear that incorporate sensors into the midsole of the shoe.

As of November 4, 2021, the shear sensor has a provisional patent filed regarding its intellectual property. This patent discusses that it is a novel sensor based on a red, green, blue (RGB) light-emitting diode (LED) which projects a cyclic illumination of RGB light onto a color pattern surface. As shear strain causes a displacement between the LED and the color pattern, the intensities of the reflected lights change due to a shift of the color pattern position. A photodiode captures the reflected light intensity at each color illumination, and this allows the displacement of the color pattern surface to be determined and consequently for the shear along two axes to be calculated. Future efforts are being made to miniaturize the sensor and adjust the color patter to allow for more precise measurement of shear stress (McGeehan et al., 2021).

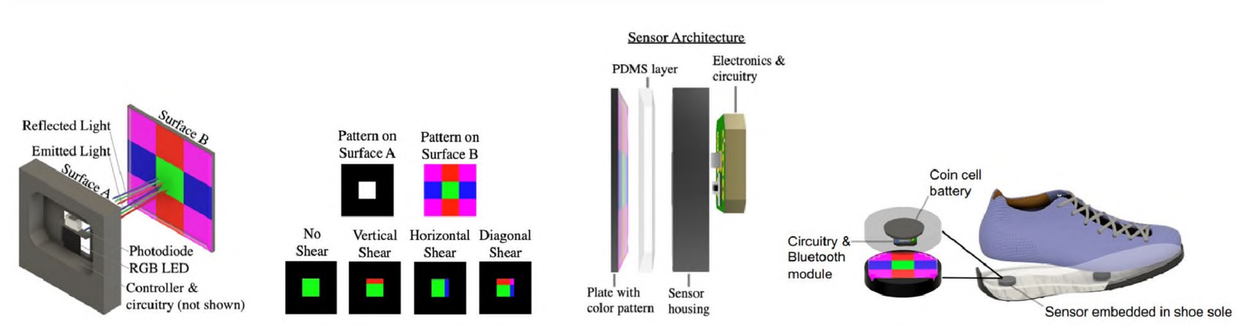


Figure 11. Displays the design and architecture of the shear sensor (McGeehan et al., 2021).

Relevant patents within the footwear space that incorporate sensors in the midsole of the shoe:

Footwear Having Sensor System – U.S. Patent No. 9763489 B2 – describes a sensor system that is adapted for use with an article of footwear and includes an insert member including a first layer & a second layer, a port connected to the insert and configured for communication with an electronic module, a plurality of force and/or pressure sensors on the insert member, and a plurality of leads connecting the sensors to the port (Amos & Weitmann, 2017).

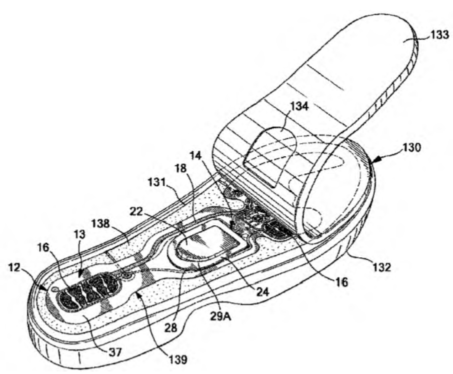


Figure 12. Displays image from *Footwear Having Sensor System* – U.S. Patent No. 9763489 B2.

Pressure Sensor, e.g. in Footwear Sole – U.S. Patent No. 2020/0182714 A1 – describes a pressure sensor, e.g. for being arranged in the sole structure of footwear, for measuring a pressure exerted by the wearer's foot using sensing cells. Each cell has a first flexible carrier film & a second flexible carrier film, the first and second carrier films being attached to one another by a spacer film having an opening (Steier, 2020).

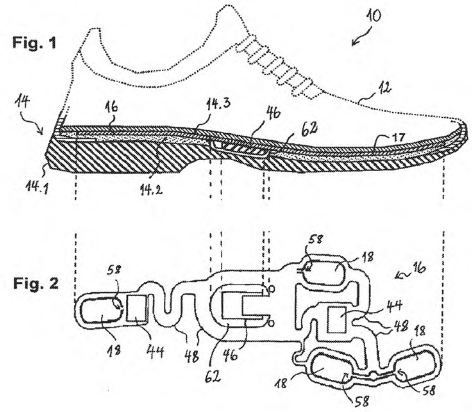


Figure 13. Displays image from *Pressure Sensor, e.g. in Footwear Sole* – U.S. Patent No. 2020/0182714 A1.

Footwear Having Sensor System – CA Patent No. 2827685 C – details footwear that includes an upper member and a sole structure, with a sensor system connected to the sole structure. The footwear contains a communication port operably connected with the sensors & configured for transmitting data regarding forces detected by each sensor in a universally (Molyneux et al., 2018).

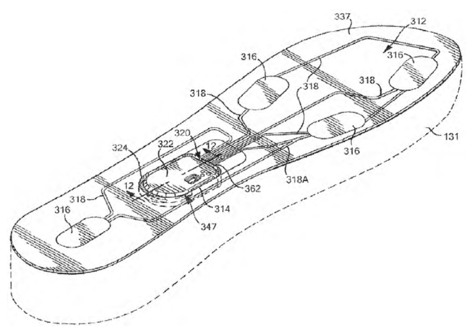


Figure 14. Displays image from *Footwear Having Sensor System* – CA Patent No. 2827685 C.

Shoe Housing – U.S. Patent No. 7596891 B2 – outlines a shoe with a sole unit that includes a recess for removably receiving a housing of an electronic assembly for an electronic pedometer, accelerometer, or speed sensor. The housing is built to receive an electronic assembly & has an outer shape corresponding to the shape of a recess formed in a shoe sole (Carnes et al., 2009).

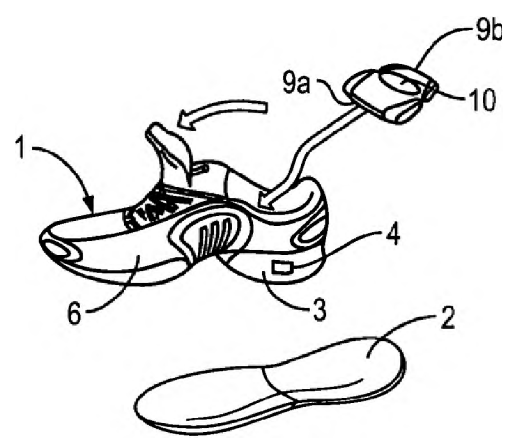


Figure 15. Displays image from *Shoe Housing* – U.S. Patent No. 7596891 B2.

Capacitive Presence Sensing Footwear – JP Patent No. 6896758 B2 – overviews footwear to sense if a foot is present in the shoe. The midsole plate is fixed within the midsole, the actuator can be inserted into the side opening of the midsole plate, the interface button is embedded in the outsole, & the lace-up engine may be coupled with one or more sensors located elsewhere in the footwear (ウォーカー、スティーブン et al., 2021).

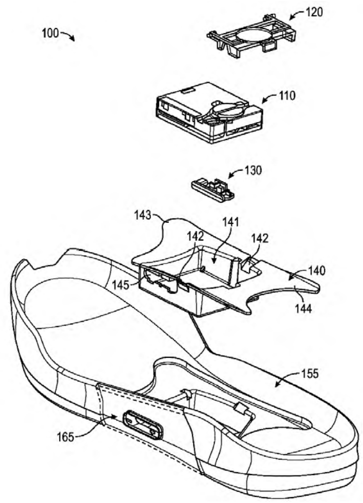


Figure 16. Displays image from *Capacitive Presence Sensing Footwear* – JP Patent No. 6896758 B2.

Footwear Having Sensor System – U.S. Patent No. 10398189 B2 – discusses a sensor system may be in an insert forming a sole member. The insert includes an airflow system including air chambers in communication with air reservoirs through air passages extending therebetween. The insert may also have a multi-layered structure, with the airflow system between the layers (Amos et al., 2019).

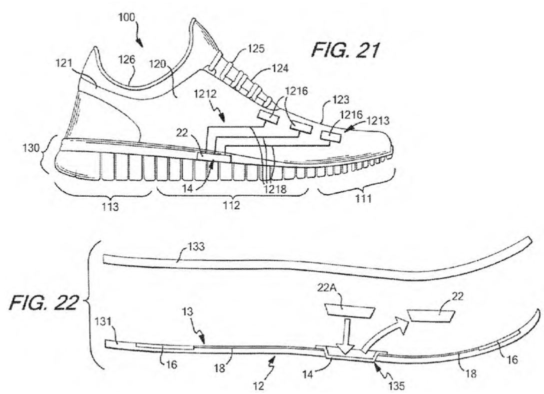


Figure 17. Displays image from *Footwear Having Sensor System* – U.S. Patent No. 10398189 B2.

Trends − Color, Graphics, and Branding

All trend research focuses on the spring and summer seasons of 2022 to 2023 because the proposed footwear products are intended to launch within this period. The "Maximalist Runner" will be a primary footwear trend during this time. This trend is influenced by the Outdoor Boom and is characterized by footwear that is built to elicit joy and promote play. Key features of these shoes include energy return soles, waterproof materials, and energy boosting colorways (Saldana, 2021a).

The main color of the trail trainer will be based in Black, while the main color of the road trainer will be based in Optic White. Black, 19-4203 TCX, and Optic White, 11-4800 TCX, are core colors that will act as a classic foundation to bring familiarity to consumers who feel cautious and are seeking comfort post-pandemic (*Global Colour S/S 22 - WGSN Fashion*, n.d.; Kostiak, 2021). Secondary colors for the footwear will be Silver Grey, 13-4201 TCX, and Volcanic Ash, 19-3912 TCX. These colors give hints of what might happen when Optic White and Black are mixed, and they will subtly provide additional intrigue to the footwear. The accent color of the trail trainer will be Lime Green, and the accent color of the road trainer will be Verdigris. Lime Green, 18-4834 TCX, will bring energy, notes of escapism, and the idea of digital futurism (Clark, 2021b). Verdigris, 13-0540 TCX, is a trans-seasonal, nostalgic color that will be used as an invigorating, digitalized shade (Clark, 2021a).

Graphics will follow the *Connected* and *Full Spectrum* trends that are projected on WGSN for S/S 2022 and 2023, respectively. The *Connected* trend explores how humanity relates to themselves and others while exploring virtual worlds. In this trend, design is less about the product and more about how it serves humanity. Specific visual nods to this trend will come from the concepts of "Light Shifts," "Connected Workouts," and "Virtual Textures." These concepts have digital, glitch, and blurred textures and prints, some of which show that technology is integrated into the product (*Active Forecast S/S 22: Connected - WGSN Fashion*, n.d.). Following the pandemic, which was a time of global constraint, the *Full Spectrum* trend is meant to evoke a collective exhale and bring an experience of extravagance to the everyday. Specifically, the concepts of "Digital Cozy," "Unnatural Nature," and "Technical Ombre" will be relevant to the proposed footwear products (Watkins, 2021).

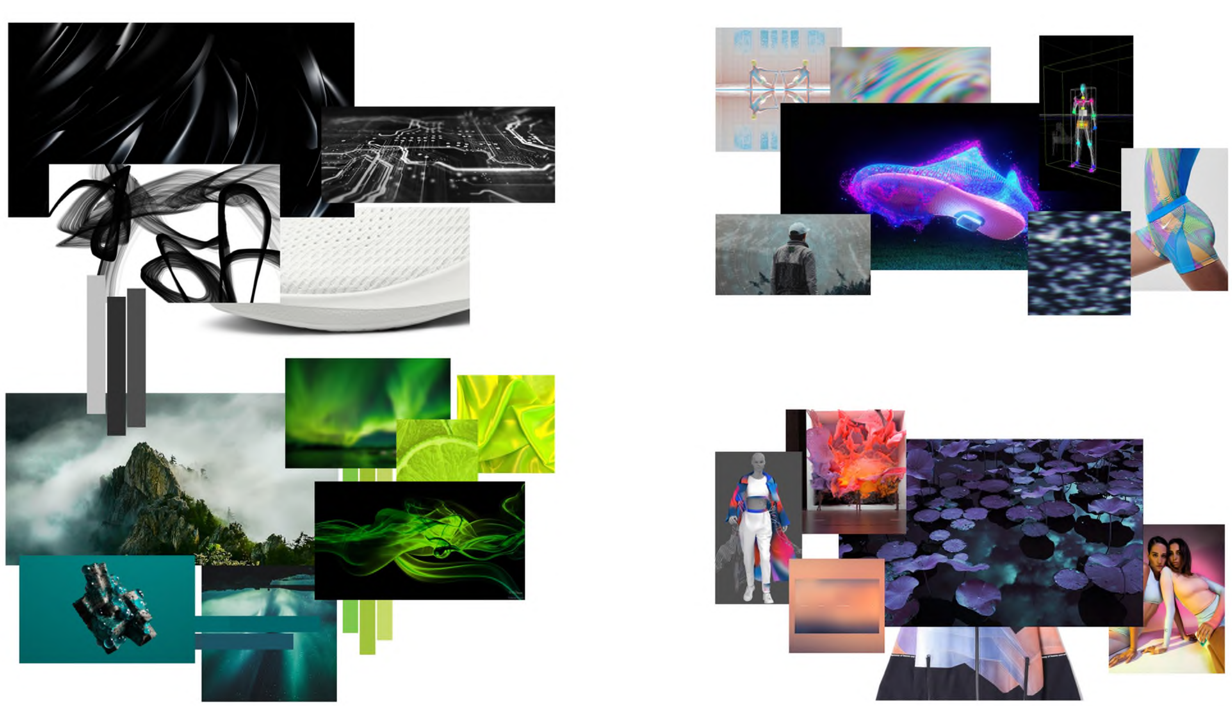


Figure 18. Displays inspirational imagery of the relevant color (left) and graphics (right) trends.

Logo and branding will play with a clash of striking and subtle. Engineered knits and TPU overlays should be used to boldly display logos. The brand name and logo are often applied in an understated fashion. Any technology that is integrated into the product should be highlighted through a callout so that the consumer understands what the footwear was built to do and how it accomplishes its goals (Saldana, 2021b).

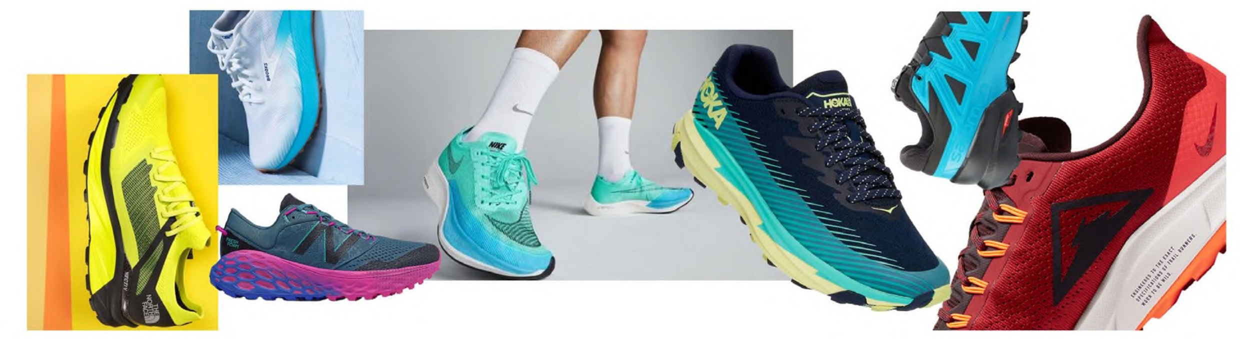


Figure 19. Displays relevant logo, branding, and technology callouts on running footwear.

Morphology & Physiology Research

Males and females have unique foot morphology and geometries that should inform how footwear products are designed for each sex. Various studies have examined the differences between female and male feet. One study stated that women's feet "are not algebraically scaled, smaller versions of male feet" (Luo et al., 2009). Additional research determined that "at the same foot length, a women's foot has a higher arch, a shallower first toe, a shorter ankle length, a shorter length of the outside ball of the foot, and a smaller instep circumference than a man's foot" (Wunderlich & Cavanagh, 2001). Another study confirmed that "the female foot has a narrower ankle width, a hallux valgus, a narrower Achilles tendon, a higher arch, and a narrower heel compared to the male foot" (Stanković et al., 2018).

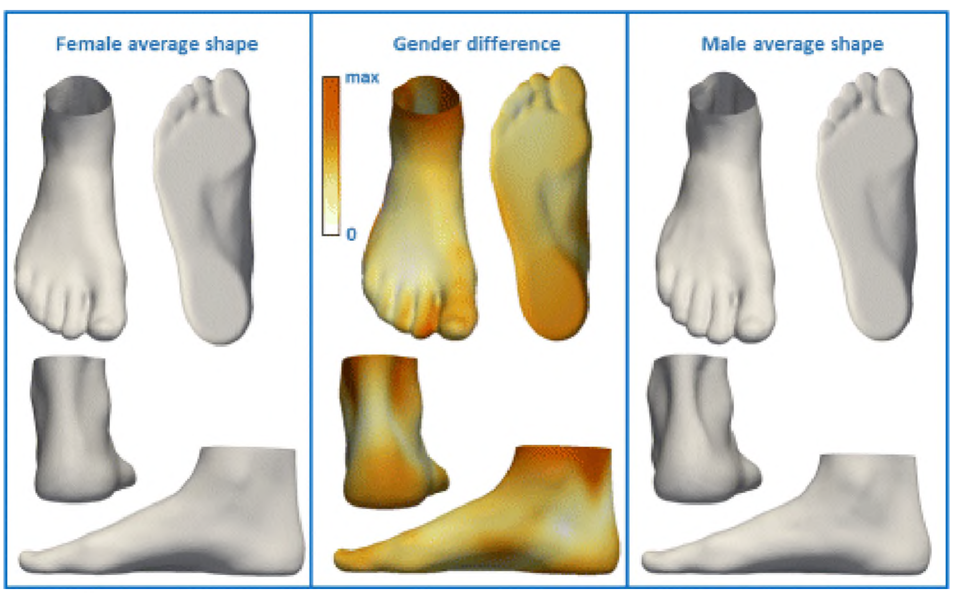


Figure 20. Visualization of the effect of sex on the foot shape. The influence of sex is represented by color-mapped Euclidean distance computed between average male foot shape and average female foot shape (Stanković et al., 2018).

In addition to unique foot morphology, there are also distinct differences in physiology between males and females. On average, females approximately have 30% lower maximum cardiac output, 25% to 50% lower maximal oxygen uptake (VO_2 max), lower blood volume, 45% less lean body mass, 11% lower hemoglobin, and 30% greater body fat percentage. These differences lead to a reduced work capacity, reduced carrying capacity of oxygen, a reduction in upper body by 40% to 60%, and weaker lower body strength by 25% (Ackerman, 2021).

For distance runners, there are three key physiological determinants which, when maximized, will improve performance. One of the most important of these physiological determinants is maximal oxygen uptake (VO_2 max) which depends on blood volume, capillary density, mitochondrial density, and stroke volume. The two other key physiological determinants for distance runners are lactate threshold, the intensity of exercise at which lactate begins to accumulate in the blood faster than it can be removed, and running economy, the oxygen uptake at submaximal running velocity (Samuels, 2018; Thompson, 2017).

Biomechanical Research

In running, proper biomechanics are vital to prevent injury, especially due to overuse, and increase performance. Runners' biomechanics are directly related to their running gait. The running gait cycle consists of the stance, swing, and float phases. The stance phase is the start of the gait cycle, and it is 40% of the cycle and includes the right heel strike, right mid stance, and right toe-off. Then the cycle progresses to the first float phase which is 15% of the cycle. Next is the swing phase which is 30% of the cycle. Finally, the second float phase is the final 15% of the cycle. When the runner's speed increases, the stance phase decreases as other phases increase (Chan & Rudins, 1994).

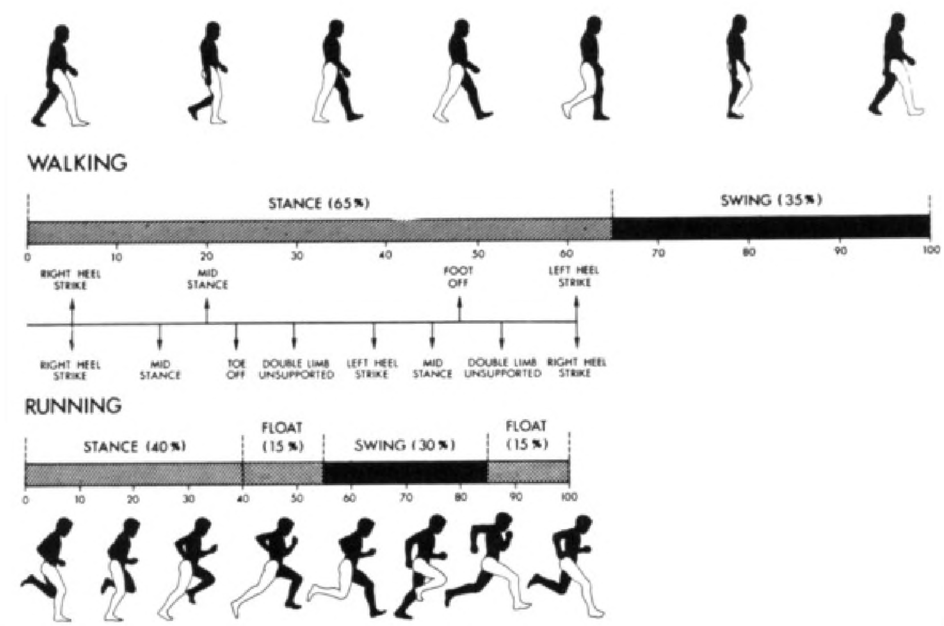


Figure 21. Displays image of the gait cycles for walking and running (Chan & Rudins, 1994).

Running biomechanics are often analyzed by examining the forces that occur between the runner and the running surface. These forces are the ground reaction forces (GRF) and include parameters of loading rate, first impact peak, second impact peak, and transient between first and second impact peaks in heel strike runners (Yu et al., 2021). The specific forces that occur include vertical force, fore and aft shear, medial and lateral shear, and torque (Chan & Rudins, 1994). Shear forces have major implications during propulsion, braking, turning, on inclines and declines, and on uneven surfaces. At impact during braking, "the foot has a horizontal velocity component of approximately 17% of the runner's forward velocity" – this horizontal component is an anteroposterior shear force which peaks at approximately half the body weight during the first part of a stance (Chan & Rudins, 1994). A similar force is developed in the opposite direction to promote forward propulsion.

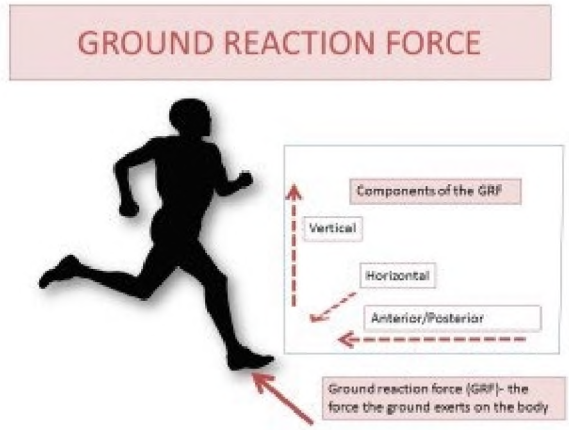


Figure 22. Displays image explaining the ground reaction forces during running (Potach, 2015).

Evaluating shear forces both between the shoe and the ground, as well as the foot and the shoe is an extremely important task because being able to optimize these forces has the potential to improve performance efficiencies, determine proper shoe fit, prevent the development of blisters or ulcers, and promote proper foot tissue health. Specifically, shear force data can be used to measure how propulsion is affected by changing various biomechanical factors of a runner's gait. Increasing the shear forces which cause propulsion will improve performance.

Additionally, reducing shear forces during braking will help reduce injury. In 2018, one study found that "runners with the highest peak braking force were almost eight times as likely to get injured than runners with the lowest peak braking force (Douglas, 2018). Previously, it was hypothesized that average vertical loading rate would show the greatest correlation with injury rate. However, measurements of vertical force were shown to have no relation to injury rate. The only significant relation to injury rate due to overuse was peak braking force. The reasoning behind this discovery is bone is not built to withstand horizontal (shear) forces nor is bone supported by joints and soft-tissue structures in a way that is meant to withstand shear forces. Bone and support structures within the lower extremities were designed to withstand vertical (compressive) forces (Douglas, 2018).

Psychological Research

There are several psychological characteristics that set distance runners apart from non-runners. Distance runners tend to have higher grit and greater resilience than non-runners. Additionally, distance runners are more likely to use positive reappraisal when regulating their emotions. Similarly, distance runners have a lower skin conductance and heart rate when viewing unpleasant images than non-runners. Another key difference is that, on average, distance runners have lower affiliative extraversion, meaning they are not as socially-warm people as non-runners (Reynolds, 2020).

Something else to consider is how knowledge of performance metrics can affect performance. Does knowing pace time change an athlete's performance? How does knowledge of other performance metrics psychologically affect the athlete? The reasons coaches have players watch game film or slow-motion analyses of target movements is so that the athlete can recognize areas of improvement and notice when they have done something correct so it can be repeated. Being able to understand what is correct, study that, actively work to improve, and then replicate it is vital to improvement. Access to information on individual performance metrics is key to learning.

However, knowledge of performance metrics during racing may negatively affect performance. One study found that "following a personalized pace might associate with higher anxiety due to uncertainty in being able to keep up with the pacer and public visibility of dropping behind" (Fullerton et al., 2017). Additionally, it was determined that a paced group had no significant differences in finish time, goal confidence, goal difficult, perceived exertion, and self-rated performance when compared to a group that was self-paced (Fullerton et al., 2017). Additionally, another study looked at the effects of self-confidence on sports performance. It found that "confidence is an important factor that distinguishes successful athletes from unsuccessful ones in terms of both their mental states as well as their performances" (Feltz, 2007).

While it is unknown how the knowledge of shear stress will affect an athlete's psychology and therefore performance, it can be concluded that athlete psychology is a complex and important factor to satisfactory performance.

Collecting Athlete Information to Determine Project Viability

Additional information will be collected to determine if distance runners are interested in the proposed footwear product. Verifying that distance runners are interested in smart training footwear will prove the viability of this project. Additionally, it is important to collect information on the average distance run each week by target athletes, how target athletes currently record their performance metrics, and which performance metrics target athletes are interested in. A questionnaire has been developed to collect this information. The content of the *Questionnaire to Investigate Distance Runners' Appetite to Measure their Performance Metrics* can be found within the Appendix.

Performance Testing Plans

To determine a baseline of where the proposed footwear project should fall in terms of function and aesthetics, competitor products will be purchased, tested, and analyzed. Three competitor products will be analyzed, the Altra Torin IQ, Nike Pegasus 38, and Nike Pegasus Trail 3 GORE-TEX. The Altra Torin IQ will provide information on how sensors can be implemented into footwear, comfortability of smart footwear, and will be the product to beat. The products to learn from regarding their high-quality performance will be the Nike Pegasus shoes. The proposed footwear project may not beat these shoes in every category, but it should shoot to be closer on the quality spectrum to these shoes than the Altra Torin IQ. All shoes will be purchased in the same size so that they can be tested by the same athletes.

Shoe	Price	Size	Colorway
Altra Torin IQ	$84	M7	Blue/Black
Nike Pegasus 38	$120	W8	Volt/Barely Volt/Black
Nike Pegasus Trail 3 GORE-TEX	$160	W8	Black/Lapis/Bright Mango/Flash Crimson

Figure 23. The Men's Altra Torin IQ.

Figure 24. The Women's Nike Pegasus 38 & Women's Nike Pegasus Trail 3 GORE-TEX.

The shoes will be tested to determine flexibility, comfort, plantar pressure differences, weight, and aesthetic preferences. All testing will be performed in the Nucleus Lab at the Portland Campus of the University of Oregon. Approximately five athletes will be recruited as wear testers. These athletes will be female runners, size Women's 8.

To test flexibility and traction, methods outlined by the Nucleus Lab and based on ASTM testing will be employed. These methods will require a force gauge. A scale will be sourced from the Nucleus Lab to measure weight. Aesthetic preferences and comfort will be assessed through a survey and verbal questioning during wear testing. Plantar pressure differences between shoes will be analyzed by utilizing ARION insoles and a treadmill. Data will be collected, quantified, then analyzed using Excel spreadsheets. Athlete feedback in the form of quotations will be used as supporting evidence. The following is an outline of the testing protocol that will be used:

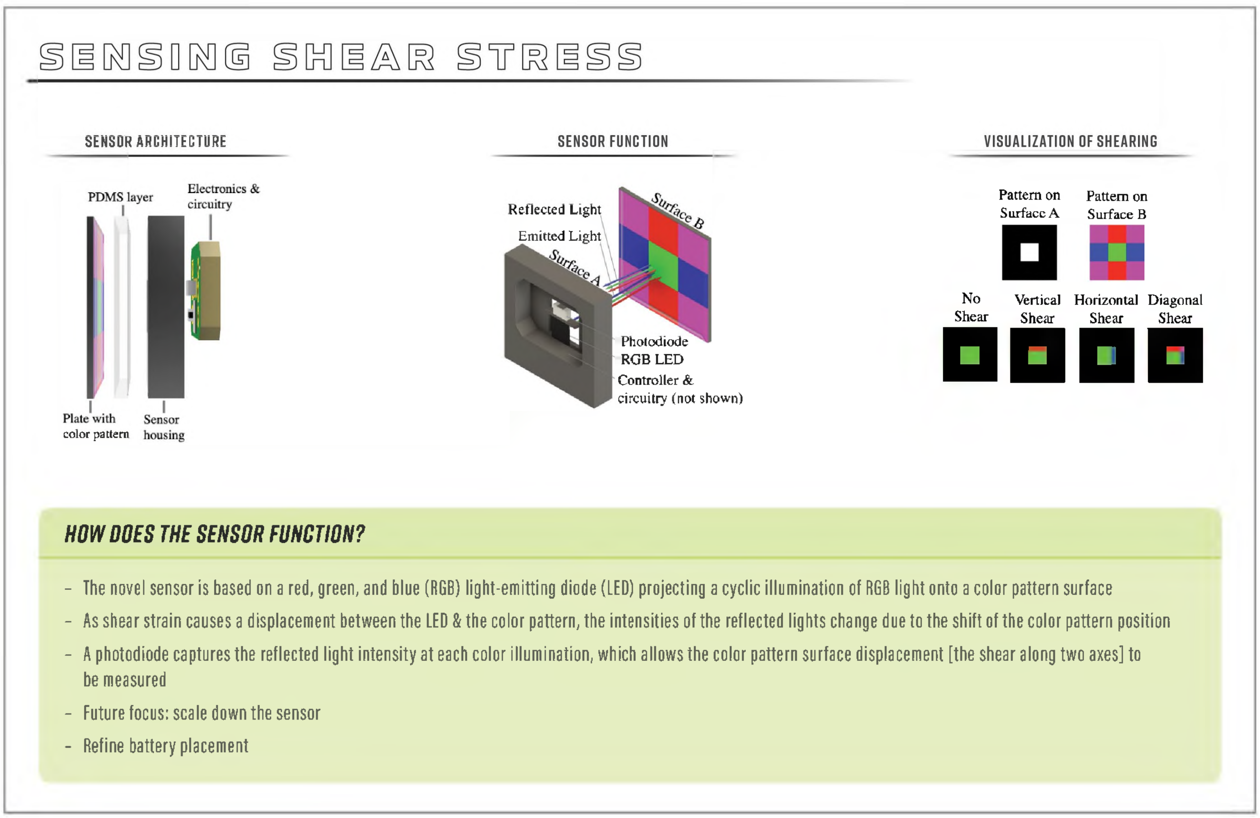
PHASE OF DATA COLLECTION	PROCEDURE	DATA COLLECTED	TIMING
– Consent form – Background information	– Subject reads & signs consent form/photo release – Subject fills out their background information in survey form	– Consent (name & signature) to participate in study & have pictures taken – Age, height, weight, shoe size, running experience, preferred running distance, average miles run per week	– 10 minutes
– Treadmill/force plate testing	– Have athlete put on test product with ARION insoles – Have athlete run on treadmill for 5 minutes at a comfortable pace for them	– Plantar pressure – Photography – Video – Verbal questioning about shoe comfort at 0 minutes, 2.5 minutes, and 5 minutes	– 10 minutes
– Survey	– Athletes fill out survey to rank function of the shoe	– Outsole traction – Flexibility/stiffness of the midsole – Cushioning – Breathability – Stability – Energy return – Fit/lockdown – Comfort: overall, tongue, lockdown, heel counter, toe box, footbed, cushioning, upper – Aesthetics	– 5 minutes
– Qualitative quotes	– Ask athlete to describe the shoe, what they like/don't like, & specifically speak on the aesthetics of the shoe	– Interview transcription	– 5 minutes

SECTION #2: WINTER TERM

Winter term focused on testing of baseline products, developing new technologies to differentiate the proposed products in the market, and providing proof of concept that the new technologies successfully achieve their goals. The following sections display slides detailing the work done throughout the term.

Description of the Sensor & Explanation of How it Works

This thesis is inspired and built around an opto-electronics based, multi-axial shear sensor designed and created by Michael McGeehan and Keat Ghee Ong from the Knight Campus at University of Oregon in conjunction with Mike Hahn from the Bowerman Sports Science Clinic. The provisional patent application is included within the Appendix. A brief and primitive description of the sensor is below.



Background Information & Project Introduction

GABI LORENZO

MECHANICAL ENGINEER & SPORTS PRODUCT DESIGNER

WHY?
- I am energized by solving complex problems and believe that great design can always be improved.
- I enjoy solving problems by investigating the intersection of technology, engineering, & design.

FUTURE GOALS
- I hope to create innovative, beautiful, and highly functional sports products for all athletes.
- I have specific interest in additive manufacturing technologies, data-driven design, & inclusive solutions for athletes of all abilities and needs.

DREAM JOB
- Innovation Footwear Mechanical Engineer or Design Engineer in the Portland area.

PROJECT BRIEF

WU TSAI HUMAN PERFORMANCE ALLIANCE
- Committed to transforming human health through the science of peak performance
- Sponsoring this project
- Six universities are the founding partners of the alliance

OPTO-ELECTRONICS BASED, MULTI-AXIAL SHEAR SENSOR
- A team from UO Eugene developed a sensor which I was asked to integrate into running footwear

GOALS

DEVELOP PATENTABLE INTELLECTUAL PROPERTY & FILE FOR PATENT

PUBLISH A PAPER ABOUT THE DESIGN OF THE SENSOR INTEGRATION

TO ACCOMPLISH THESE GOALS, AN IRB WAS CREATED & APPROVED

THE TEAM

UO PORTLAND

SPORTS PRODUCT DESIGN
WHITE STAG

GABI LORENZO

SUSAN SOKOLOWSKI

UO EUGENE

BIOMECHANICS
BOWERMAN SPORTS SCIENCE CENTER

MIKE HAHN

BIOMECH. & ENGR.
BSSC & KNIGHT CAMPUS

MICHAEL MCGEEHAN

ELECTRICAL ENGINEERING
KNIGHT CAMPUS

GHEE KEAT ONG

HOW COULD WE ENGINEER AN INNOVATIVE METHOD OF MANUFACTURING PERFORMANCE RUNNING FOOTWEAR THAT INTEGRATES A SHEAR SENSOR TO ANALYZE THE FOOT-SHOE INTERFACE OF FEMALE DISTANCE RUNNERS?

PROJECT IMPORTANCE

WHY SHEAR STRESS?

- Measuring shear stress at the foot-shoe interface is extremely difficult & has not been done before, especially not outside of a laboratory

BENEFITS OF MEASURING SHEAR

- Could provide opportunities to improve performance efficiencies & biomechanics
- Major implications for investigating the foot's tissue health, as well as determining proper shoe fit

TARGET MARKET

- First Launch: Biomechanists & Sports Product Companies doing research
- Second Launch: Elite Female Athletes, Coaches, & Clinicians
- Third Launch: Athletes looking to improve their performance with the use of technology
- Approximately 31,500 athletes & 40,000 clinicians, & over 1000 companies

Baseline Product Testing, Performance Metrics, & Athlete Insights

BENCHMARK PRODUCTS

TORIN IQ — $220

ALTRA, MEN'S 7

- Collects data on impact force & location, contact time, & cadence to improve efficiency
- Interfaces with an app via Bluetooth for on-the-run feedback with live coaching
- Replaceable internal battery for usability
- The first commercially-available "smart shoes" released in 2017, no longer available from Altra

PEGASUS TRAIL 3 — $160

NIKE, WOMEN'S 8

- Gore-Tex layer to keep water out & feet dry
- Dynamic fit band system through the midfoot for secure support & lockdown
- Increased traction at the heel & toe for grip going uphill or downhill
- Nike React tech is lightweight & durable while offering a smooth, responsive ride

PEGASUS 38 — $120

NIKE, WOMEN'S 8

- Mid-level cushion for tons of energy return & comfort on runs of any length
- Mesh upper for ultimate breathability
- Air Zoom unit at the forefoot to create a responsive bounce
- Comfortable midfoot webbing to keep the foot snug & secure throughout the gait cycle

SWOT ANALYSIS

	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
UPPER	- Soft sandwich mesh with thick, looped eyelets that provide great lockdown without hot spots - **Conforms well to the foot & provides stability** - Gusseted tongue for better lockdown - Non-slip laces with improved lock down through throat geometry	- **Plush tongue padding & sandwich mesh trap heat & sweat** - Sometimes fit is too narrow which doesn't work well for wider feet; other times fit is too wide which doesn't provide proper lockdown - Toe box volume is often too big or too small	- **Reduce the layering of the upper to create better ventilation & breathability** - Potentially apply a DWR finish as spring is often a wet season (but this may not be needed as this is for summer as well)	- Reducing the layering of the upper will most likely reduce the comfort & stability of the upper - DWR finish is probably not needed and would just add cost
SOCKLINER	- Inexpensive - Fits the shoe interior well - **Deep heel cup eliminates slippage**	- Not anti-microbial or odor resistant	- Addition of anti-odor or sweat wicking technology - Insoles contoured to the unique foot morphology due to sex	- Increasing technology in the insole will increase price - Insoles are often overlooked & technology in this area is often viewed as unnecessary
MIDSOLE	- Forefoot air unit increases comfort - **Embedded S-shaped, full-length nylon plate provides comfort, impact attenuation, & solid energy return** - Rocker technology helps the foot move through the proper biomechanical gait	- Too much cushioning can slow the runner down - Requires a break-in period to be comfortable - Single density foam - **No rocker technology** - No rock or energy return plate	- Variable density cushioning to specifically cater to the individual cushioning needs for different areas of the foot - **Addition of sensor technology** - Full-length energy plate for a faster midsole	- Increasing technology in the midsole will increase price - Including a sensor may impact comfort and will increase weight
OUTSOLE	- Made of hard-wearing, durable rubber that resists abrasion - **Visually-pleasing outsole design** - **Decent traction performance** - Lightweight design	- **Traction is below average on wet surfaces due to the hard rubber outsole material** - Outsole doesn't fully protect the foam midsole which can cause damage to the foam when running on a road that has debris	- Redesign the outsole & traction pattern to provide better grip on wet surfaces - **Develop a full-length traction pattern that is designed specifically for heel-strikers**	- Creating an outsole designed specifically for wet surfaces may impact the performance of the outsole on dry surfaces as well as the durability of the outsole - A full-length traction pattern may add unnecessary weight

PERFORMANCE ATTRIBUTES

"FUNCTIONAL COMFORT"

THE FOOTWEAR NEEDS TO INTEGRATE A SHEAR SENSOR
WITHOUT COMPROMISING UNDERFOOT COMFORT

OVERALL WEIGHT OF THE SHOE
- Increasing the weight of a shoe will affect running efficiency & decrease performance [100g+ slows down athlete by 1%]

DUROMETER & FLEXIBILITY OF THE SOLE UNIT
- If the sensor does not allow the sole unit to flex with a similar amount of force, then this will negatively affect performance

PLANTAR PRESSURE DISTRIBUTION
- Plantar pressure hot spots originating adjacent to or at sensor placement will affect comfort

OUTSOLE TRACTION
- Outsole traction is key to helping the athlete feel confident & comfortable in the footwear

WEIGHT

DATA COLLECTION

1 INSPECT THE SHOE
- Shoe is clean; insole & laces are present

2 WEIGH THE SHOE
- Zero the scale; place the shoe on the scale

WEIGHT RESULTS

244 GRAMS	259 GRAMS	245 GRAMS

DUROMETER

DATA COLLECTION

1 PREP THE DUROMETER
- Press indentor on surface 20 times

2 TAKE THE MEASUREMENT
- Select a flat surface
- Press the indentor down perpendicularly until the presser foot touches the surfaces

3 REPEAT
- Take multiple measurements for each midsole
- Take multiple measurements for each outsole

MIDSOLE RESULTS

31.8 SHORE A	29.1 SHORE A	31.8 SHORE A

OUTSOLE RESULTS

61.0 SHORE A	67.3 SHORE A	62.0 SHORE A

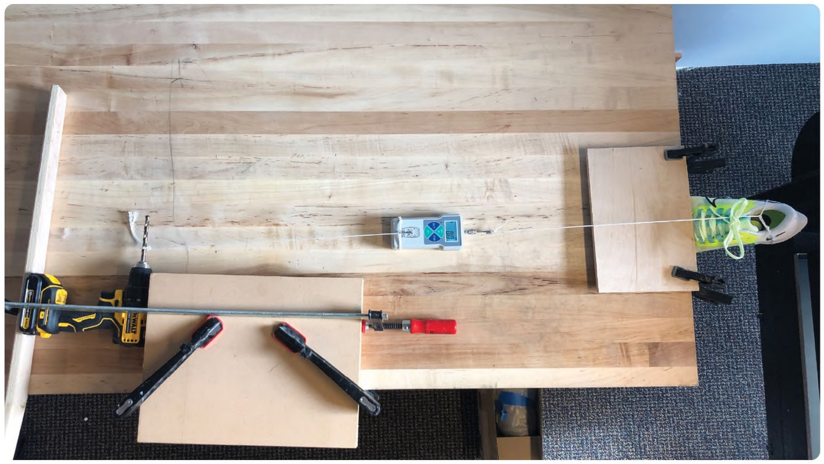
SOLE UNIT FLEXIBILITY

DATA COLLECTION

1 *CLAMP THE SHOE DOWN*
- Clamp at forefoort breaking point of shoe
- Set force gauge to measure peak force

2 *APPLY FORCE TO FLEX*
- Use drill to pull heel to 90 degrees flexion
- Use drill at a controlled speed
- Ensure that force gauge stays in place

3 *REPEAT & RECORD*
- Record the peak force in Newtons
- Repeat 5 times for each shoe (R & L)



TORIN IQ RESULTS

35.6
NEWTONS

PEGASUS TRAIL 3 RESULTS

30.0
NEWTONS

PEGASUS 38 RESULTS

29.0
NEWTONS

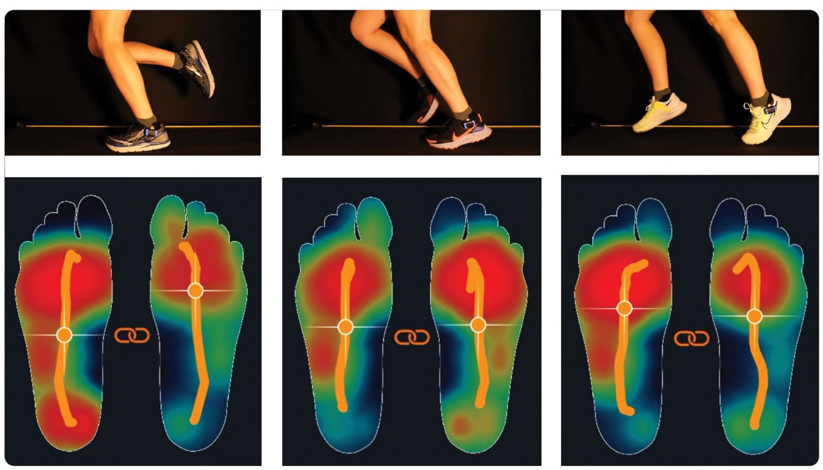
PLANTAR PRESSURE

DATA COLLECTION

1 *PLACE ARION INSOLES*
- Put insoles in shoe & shoes on athletes
- Make sure app & insoles are functioning

2 *TREADMILL RUN*
- Use app to record a 5 minute treadmill run
- Ask athletes questions regarding comfort at the 2.5 minute & 5 minute marks

3 *REPEAT & RECORD*
- Plantar pressure distribution videos & graphs
- Repeat for all test footwear



TORIN IQ IMPULSE

219
N*s

PEGASUS TRAIL 3 IMPULSE

210
N*s

PEGASUS 38 IMPULSE

223
N*s

WEAR TEST PERCEPTIONS

	COMFORT	CUSHIONING	VENTILIATION	ENERGY RET.	AESTHETICS	OVERALL*
	5.6 /10	4.4 /10	6.0 /10	2.9 /10	2.5 /10	4.8 /10
	7.7 /10	6.2 /10	5.8 /10	6.4 /10	7.4 /10	7.0 /10
	7.3 /10	7.8 /10	5.4 /10	7.5 /10	6.6 /10	6.9 /10

OF PARTICIPANTS 05

*OVERALL RANKING IS DETERMINED BY AVERAGING THE WEAR TESTERS' RANKS OF PERCEIVED COMFORT AT BOTH 2.5 MINUTES & 5 MINUTES, TRACTION, CUSHIONING, STABILITY, BREATHABILITY, ENERGY RETURN, FIT, & AESTHETICS.

TRACTION

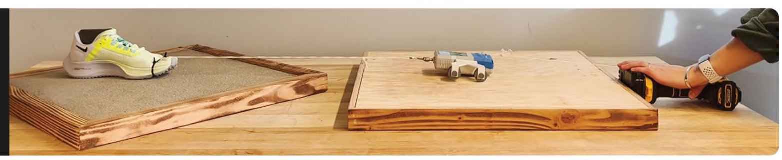
DATA COLLECTION

1 PLACE WEIGHTS
- Put 4 flat weight plates inside the shoe
- 2 weights at forefoot, 2 in the heel area

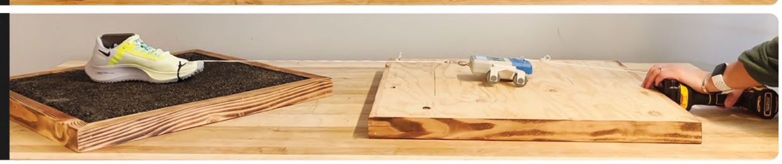
2 SET FORCE GAUGE
- Use drill to pull shoe across the surface
- Use drill at a controlled speed
- Ensure that force gauge stays in place

3 REPEAT & RECORD
- Record the peak force
- Repeat for all test footwear

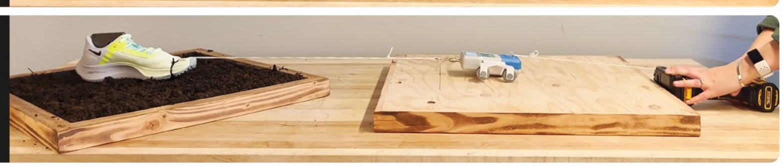
CONCRETE



ASPHALT



WET DIRT



	Shoe 1	Shoe 2	Shoe 3
CONCRETE RESULTS	12.1 NEWTONS	12.7 NEWTONS	12.5 NEWTONS
ASPHALT RESULTS	12.0 NEWTONS	12.9 NEWTONS	12.5 NEWTONS
WET DIRT RESULTS	13.4 NEWTONS	15.8 NEWTONS	13.5 NEWTONS

IMPROVING PERFORMANCE

"FUNCTIONAL COMFORT"

THE FOOTWEAR NEEDS TO INTEGRATE A SHEAR SENSOR **WITHOUT COMPROMISING UNDERFOOT COMFORT**

AVG. RANKING

COMFORT	AESTHETICS	OVERALL*
6.8 /10	5.5 /10	6.2 /10
<5% ACCEPTABLE PERCENT DIFFERENCE -	>5% ACCEPTABLE PERCENT DIFFERENCE +	<5% ACCEPTABLE PERCENT DIFFERENCE -

AVG. BASELINE RESULTS

SHOE WEIGHT	SOLE DUROMETER	SOLE UNIT FLEXIBILITY	IMPULSE	TRACTION
249.3 GRAMS	34 / 65 MID / OUTSOLE SHORE A	31.5 NEWTONS	217.0 N*s	13.0 NEWTONS
<5% ACCEPTABLE % DIFFERENCE +/-	<3% ACCEPTABLE % DIFFERENCE +/-	<5% ACCEPTABLE % DIFFERENCE +/-	<3% ACCEPTABLE % DIFFERENCE +/-	<5% ACCEPTABLE % DIFFERENCE +/-

USER INSIGHTS

OF PARTICIPANTS 129

"RUNNERS WILL ALWAYS PRIORITIZE A SHOE'S PERFORMANCE OVER ANY SMART FEATURES"

POTENTIAL CONCERNS WITH SMART RUNNING FOOTWEAR ACCORDING TO THE PARTICIPANTS

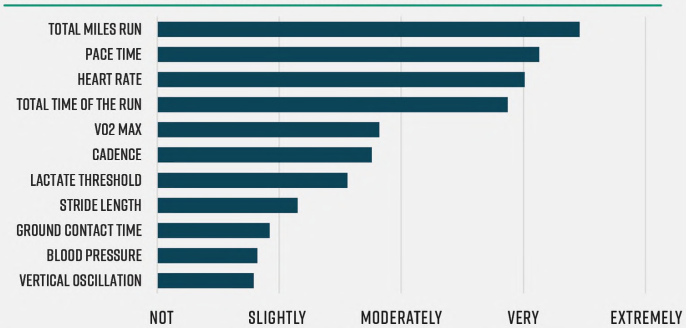
1. DECREASE IN PERFORMANCE
2. COMFORT
3. RELIABILITY
4. WEIGHT
5. PRICE
6. DURABILITY

83% OF PARTICIPANTS TRACK THEIR PERFORMANCE METRICS

55% OF PARTICIPANTS ARE INTERESTED IN A SMART TRAINING SHOE

35 MILES BY PARTICIPANTS FOR TRAINING PURPOSES AVERAGE MILEAGE RUN PER WEEK

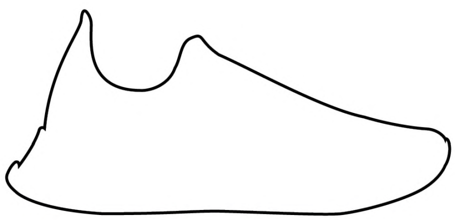
WHICH PERFORMANCE METRICS ARE MOST IMPORTANT TO RUNNERS?

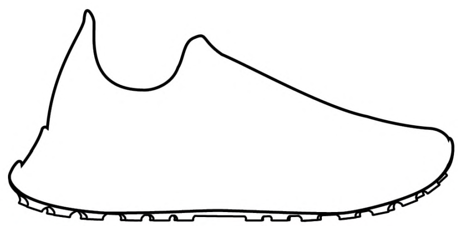


Proof of Concept

INITIAL LAUNCH – JUNE 2022

TARGETS BIOMECHANISTS & SPORTS PRODUCT DESIGN COMPANIES.





ROAD & TRAIL FOOTWEAR DESIGNED TO MEET THE NEEDS OF NEUTRAL, FEMALE DISTANCE RUNNERS

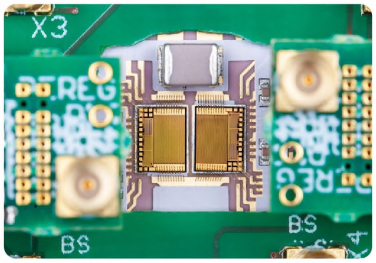
- Neutral runners are defined as heel strikers with normal gait
- The female focus will help alleviate the gap in research between female & male athletes

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
WEEK 4	24	25	26 MIND MAP OUTDOOR RETAILER	27 ATTEND OR OUTDOOR RETAILER MATERIALS SOURCING	28 ATTEND OR OUTDOOR RETAILER MATERIALS SOURCING	29 TRIP REPORT OUTDOOR RETAILER	30 HW 7 MATERIALS
WEEK 5	31 HW 7 DUE WEAR TEST (2.3) SOURCING	1 TRACTION TESTS WEAR TEST (4)	2 MIDTERM REV. EQ TRAINING	3 BRAINSTORM (2 HR) SANDWICHES (2 HR) SANDWICH PROTOTYPES & JIG	4 BRAINSTORM (1 HR) SANDWICHES (2 HR) JIG (2 HR) SANDWICH PROTOTYPES & JIG	5 SKETCH UPPER (2 HR) SKETCH SOLE UNIT (2 HR) SILHOUETTE	6 PRESENTATION/HW 8
WEEK 6	7 HW 8 DUE SCAN FEET/LAST LAST DEVELOPMENT	8 DEVELOP IN RHINO HW 9 LAST DEVELOPMENT	9 HW 9 DUE BASIC UPPER PATTERN SCAN ON LAST	10 SENSOR TESTS	11 BRAINSTORM (1 HR) SW / MOLDS (3 HR) SANDWICH & FULL PROTOTYPES	12 MOLD / ASSEMBLE SW / FULL SOLE (4 HR) SANDWICH & FULL PROTOTYPES	13 PRESENTATION/HW 10
WEEK 7	14 HW 10 DUE REVISE SILHOUETTE SKETCH / MODEL	15 3D MODEL MIDSOLE SKETCH / MODEL	16 HW 11 DUE	17 SENSOR TESTS	18 3D MODEL FINALIZE MIDSOLE MODEL / PRINT	19 PRINT MIDSOLE MOLD MODEL OUTSOLE MODEL / PRINT	20
WEEK 8	21 HW 12 DUE PRINT OUTSOLE MOLD PRINT / MOLD / MAKE	22 MOLD MIDSOLE SEW UPPER PRINT / MOLD / MAKE	23 HW 13 DUE PRINT / MOLD / MAKE	24 MOLD OUTSOLE SEW UPPER PRINT / MOLD / MAKE	25	26 BUFFER	27 BUFFER
WEEK 9	28 HW 14 DUE BUFFER						

TRAVEL TO EUGENE — OUT-OF-STATE TRAVEL — DUE DATE — MATERIALS — INTEGRATION IDEATION — REST OF SHOE IDEATION

DELIVERABLES
- W8 TRAIL: FULL CAD WITH PROTOTYPE
- W8 ROAD: FULL CAD WITH PROTOTYPE
- SOURCED MATERIALS
- VALIDATION OF SENSOR INTEGRATION

NEW TECHNOLOGIES



TAU-TECH x FUSED INTEGRATION

- TAU-TECH is a sensor which accurately measures multi-axial shear stress at the foot-shoe interface [>0.95 R-Squared value when sensor is integrated]
- TAU-TECH records data via Bluetooth to a user-friendly app
- FUSED imperceptibly integrates the sensor into the sole unit with no plantar pressure hot spots

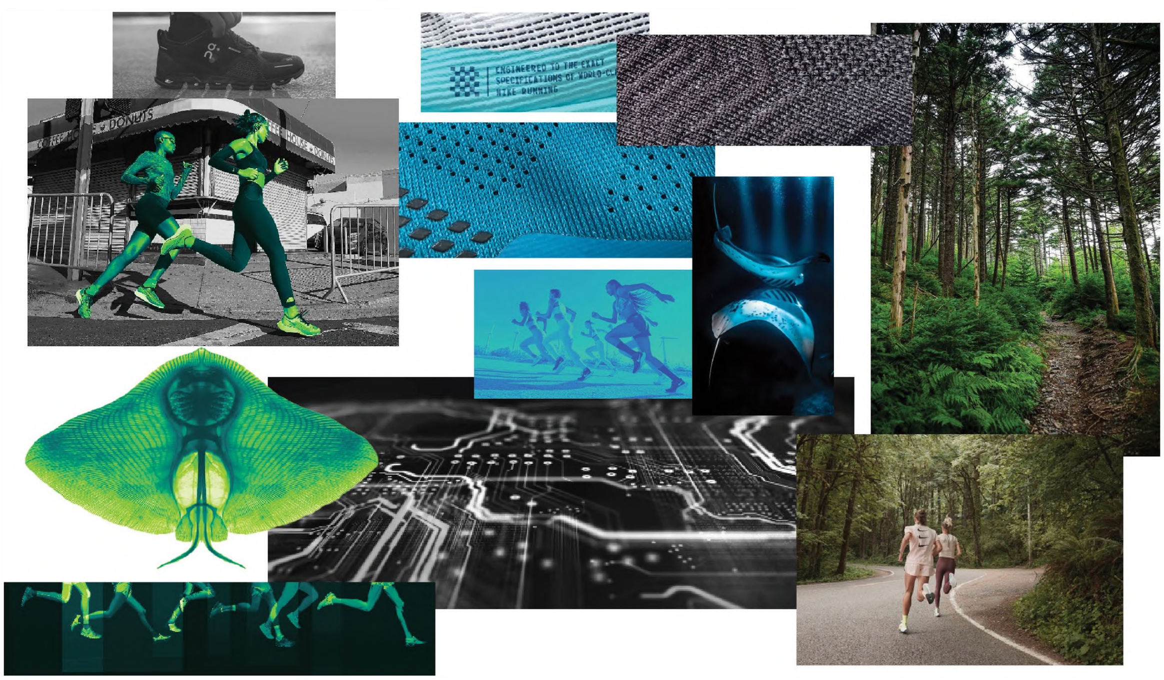
IMPULSE MIDSOLE

- IMPULSE is lightweight, provides high-energy return, has dialed-in flexibility & cushioning to protect foot while keeping it comfortable
- Within 5% difference of competitors' flexibility
- Within 5% difference of competitors' weight
- Within 5% difference of athlete's perception of competitor's comfort

TOTALIS OUTSOLES

- TOTALIS traction technology provides confident grip in wet conditions
- TOTALIS-ROAD focuses providing dry & wet pavement grip
- TOTALIS-TRAIL focuses on dry & wet trail conditions [dirt, mud, gravel, roots]
- >5% difference from traction

MOOD BOARD



MATERIALS & MANUFACTURING

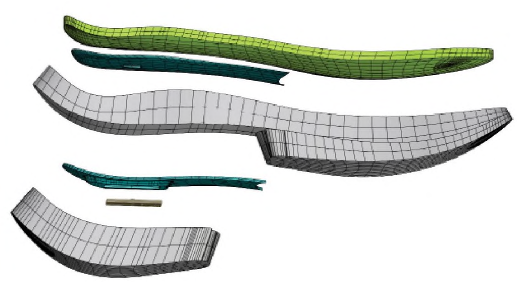
UPPER

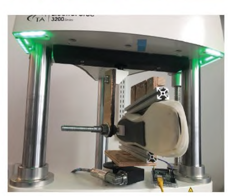
ROAD MATERIALS	TRAIL MATERIALS	STITCHING
WHITE SPACER MESH 100% POLYESTER, KNIT, 3MM THICK, 350 GSM	**BLACK SPACER MESH** 100% POLYESTER, KNIT, 3MM THICK, 350 GSM, DWR FINISH	**STROBEL**
PROTECTIVE FILM BEMIS TL644 - FORMFIT, ELASTOMERIC POLYURETHANE	**PROTECTIVE FILM** BEMIS RS3500 - RAINBOW, ELASTOMERIC POLYURETHANE	**ZIG-ZAG**
BLACK KNIT LINING 100% POLYESTER + OPEN CELL PU FOAM FOR PADDING (4MM THICK)	**BLACK KNIT LINING** 100% POLYESTER + OPEN CELL PU FOAM FOR PADDING (4MM THICK)	**COVERSTITCH**

SOLE UNIT

MIDSOLE	ENERGY PLATE	OUTSOLE
EVA FOAM INJECTION MOLDED & ADHERED WITH BARGE CLEAR TF	**THERMOPLASTIC POLYURETHANE** INJECTION MOLDED	**CARBON RUBBER** HYDRAULICALLY HEAT PRESSED & ADHERED WITH BARGE CLEAR TF
FLEX-IT! FOAM 17 SMOOTH ON EXPANDING POLYURETHANE FOAM	**ONYX SLOW LIQUID PLASTIC** SMOOTH CAST MERCURY-FREE URETHANE RESIN, ULTRA-BLACK	**REOFLEX 60** SMOOTH ON URETHANE RUBBER, DYED WITH IGNITE FLUORESCENTS

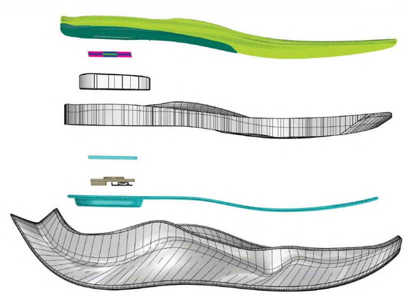
ROAD SOLE UNIT IDEATION

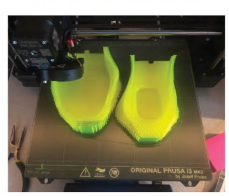


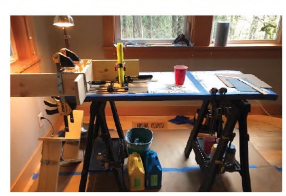


ROAD UPPER IDEATION

TRAIL SOLE UNIT IDEATION

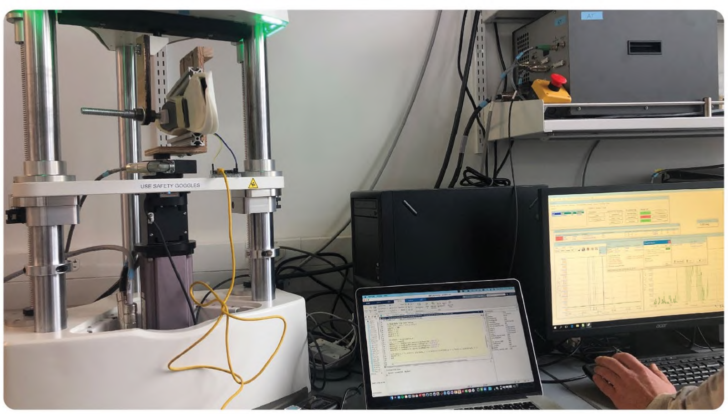


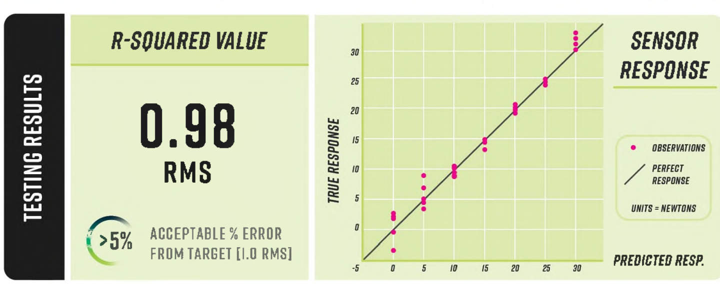


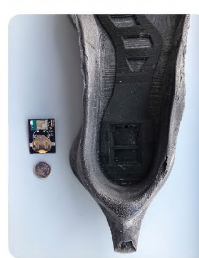


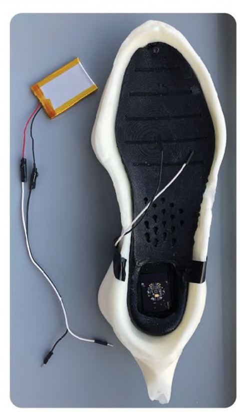
TRAIL UPPER IDEATION

FUSED INTEGRATION TESTING









IMPULSE MIDSOLE TESTING

AVG. TESTING RESULTS

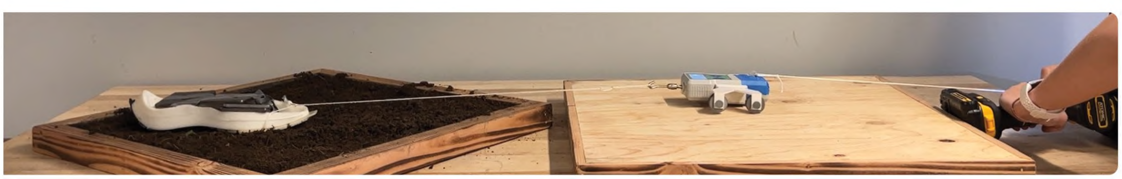
DUROMETER OF THE FOAM	ROAD SHOE WEIGHT	TRAIL SHOE WEIGHT	SOLE UNIT FLEXIBILITY
29.9 SHORE A	447 GRAMS	454 GRAMS	29.7 NEWTONS
2% LESS THAN NIKE COMPETITORS [30.4]	79% GREATER THAN COMPETITORS [249 G]	82% GREATER THAN COMPETITORS [249 G]	5% LESS THAN COMPETITORS [31.5 N]

*PROTOTYPING MATERIALS ARE HEAVIER THAN STANDARD FOOTWEAR MATERIALS

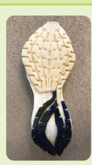
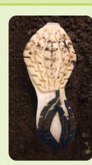
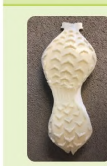
TOTALIS TRACTION TESTING

CONCRETE

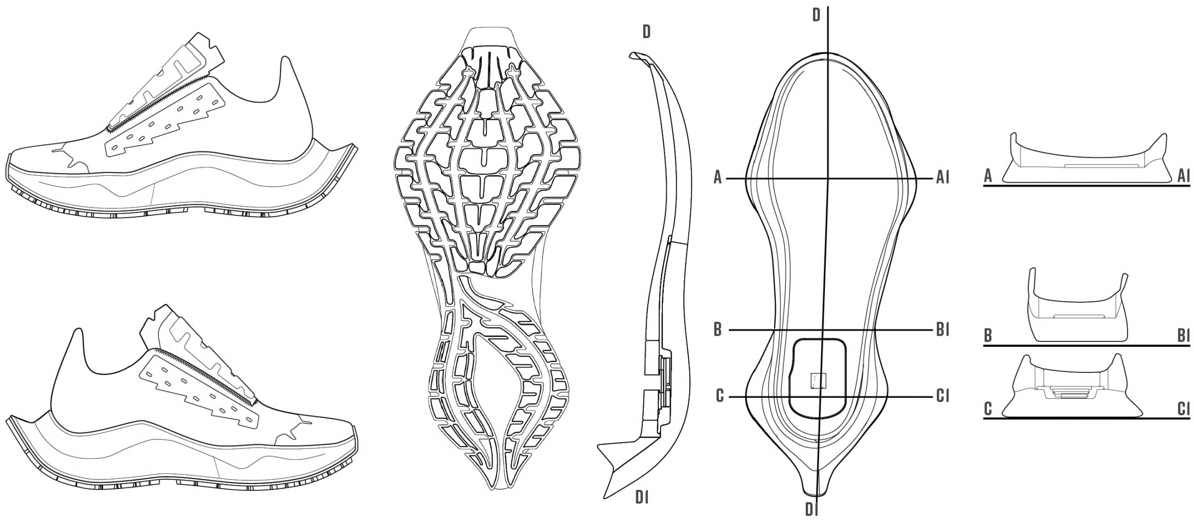
WET DIRT



AVG. TESTING RESULTS

TOTALIS ROAD TRACTION		TOTALIS TRAIL TRACTION	
 13.7 NEWTONS	 14.8 NEWTONS	 12.7 NEWTONS	 15.0 NEWTONS
10% GREATER THAN COMPETITORS [12.4 N]	4% GREATER THAN COMPETITORS [14.2 N]	2% GREATER THAN COMPETITORS [12.4 N]	6% GREATER THAN COMPETITORS [14.2 N]

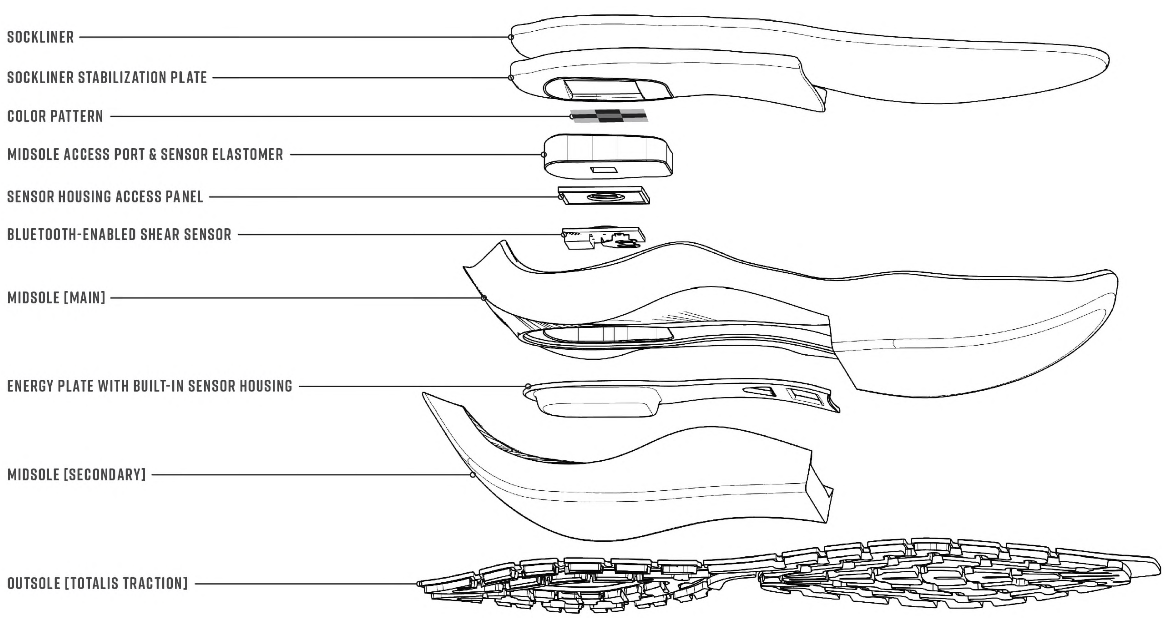
TAU ROAD



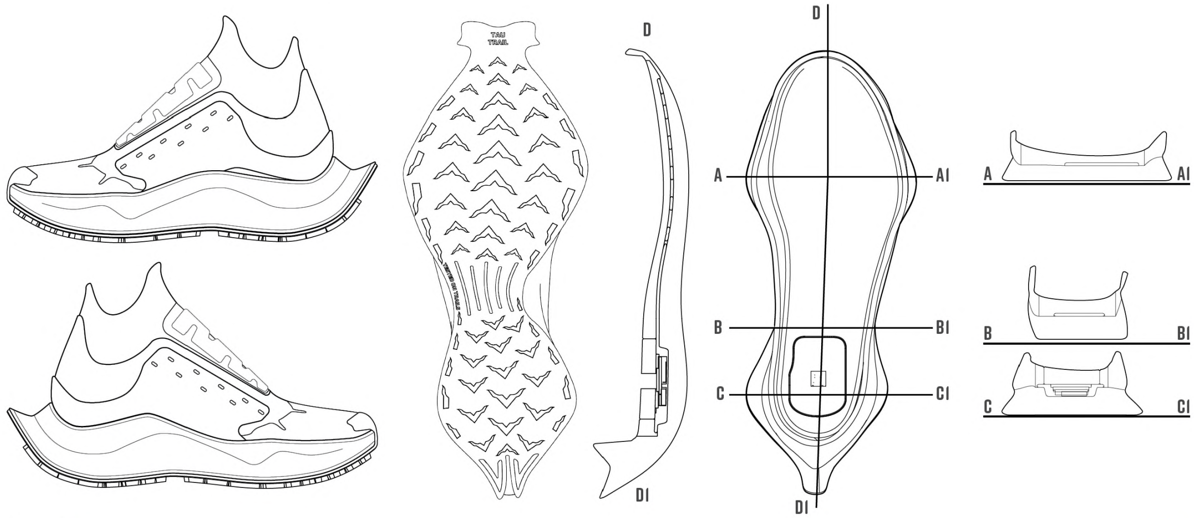
FEATURES

- **LITE-DRY UPPER —** features lightweight, protective films to keep water out & zoning for ultimate breathability
- **MONO-FLAP TONGUE —** decreased debris entry with flexible padding to enhance comfort
- **IMPULSE MIDSOLE —** contains ultra-lightweight cushioning with a partial-length, flexible plate for high energy return with minimum weight
- **TOTALIS-ROAD TRACTION —** provides a confident grip on wet & dry roads
- **TAU-TECH SENSOR —** measures multi-axial shear stress & records the data via Bluetooth to allow athletes to analyze the shear forces on their feet

ROAD SOLE UNIT



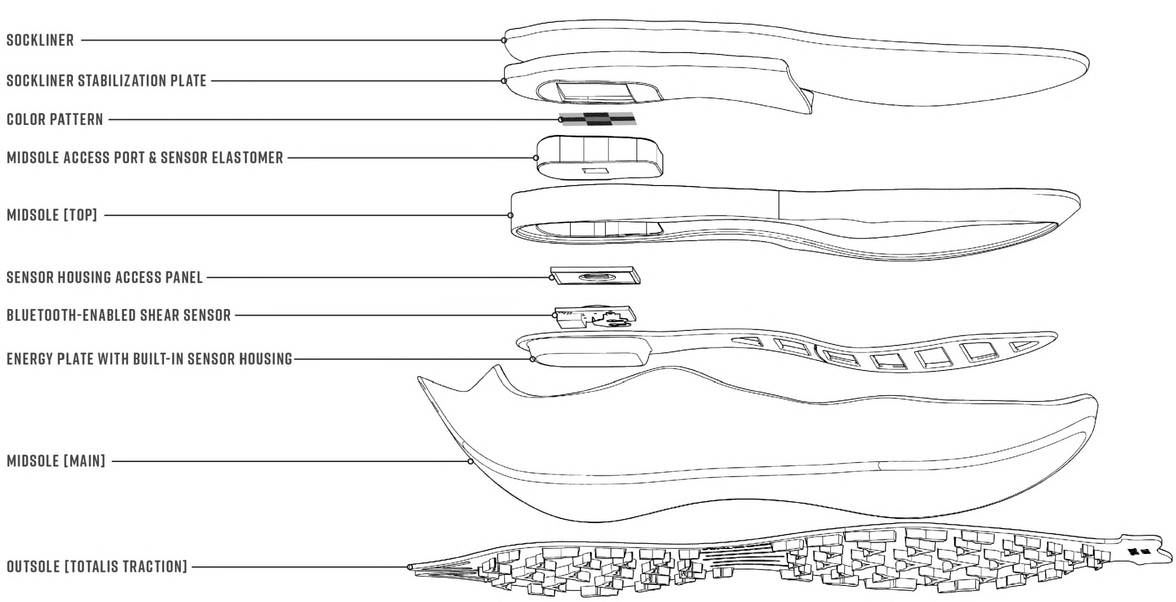
TAU TRAIL



FEATURES

- **ULTRA-DRY UPPER** — features extended protective films to keep water out & zoning for ultimate breathability
- **MID-LENGTH BOOTIE** — for decreased debris entry with flexible padding to enhance comfort
- **IMPULSE MIDSOLE** — contains ultra-lightweight cushioning with a full-length, flexible plate for high energy return
- **TOTALIS-TRAIL TRACTION** — provides a confident grip with 4mm lugs that bite wet & dry trails
- **TAU-TECH SENSOR** — measures multi-axial shear stress & records the data via Bluetooth to allow athletes to analyze the shear forces on their feet

TRAIL SOLE UNIT



WHAT'S NEXT?

FUTURE IMPROVEMENTS

AESTHETICS & BRANDING
DEVELOP LOGO, EXTEND COLORWAYS, PACKAGING, ETC.
CREATE A COHESIVE COLLECTION.

SENSOR UPDATES
UPDATE THE BATTERY, WHICH REQUIRES CHANGES TO THE SENSOR HOUSING. IMPROVE UNDER-FOOT COMFORT OF HOUSING.

UPPER DEVELOPMENT
DEVELOP THE UPPERS MORE FULLY WITH TRIMES, SUBLIMATION PRINTING, ADDITIONAL AESTHETICS, ETC.

LEARNINGS & NEXT STEPS

MOLD CREATION
3D PRINTING THE MOLD VS. CREATING MOLD FROM A 3D PRINTED PART. BETTER RESULTS ACHIEVED BY 3D PRINTING THE MOLD.

SENSOR TESTING & JIG DEVELOPMENT
VARIOUS WAYS TO VALIDATE THE SENSOR WITH THE SHOE. DEVELOPING THE JIGS FOR TESTING IS EXTREMELY IMPORTANT.

WEAR TESTING
CREATE FULLY-WEARABLE SHOES & HAVE ATHELTES EVALUATE UNDER-FOOT COMFORT. MAKE IMPROVEMENTS BASED ON FINDINGS.

SECTION #3: SPRING TERM

Spring term focused on refining the storytelling of the project, finalizing the design, ideating on the aesthetics of the design, prototyping, testing and validating the design both with athletes and experts, and creating a presentation to defend the thesis. The following are slides of a process book detailing the work done throughout the term.

TAU TRAINERS

SENSOR-EQUIPPED, PERFORMANCE RUNNING FOOTWEAR FOR FEMALE DISTANCE RUNNERS

GABI LORENZO

2022 CAPSTONE THESIS

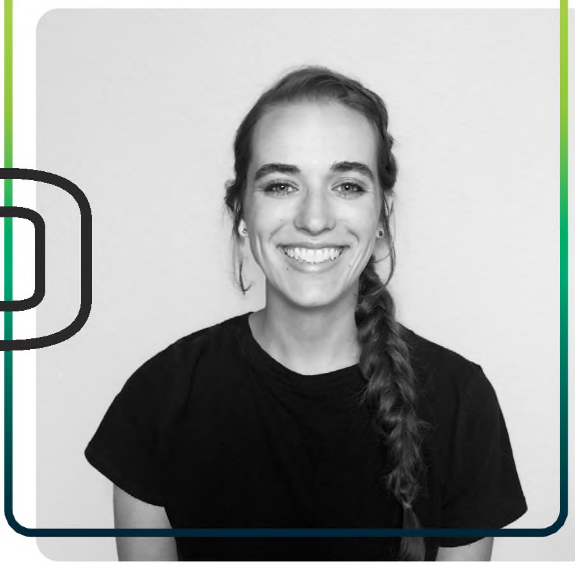
U.O. M.S. SPORTS PRODUCT DESIGN

TABLE OF CONTENTS

INTRODUCTION

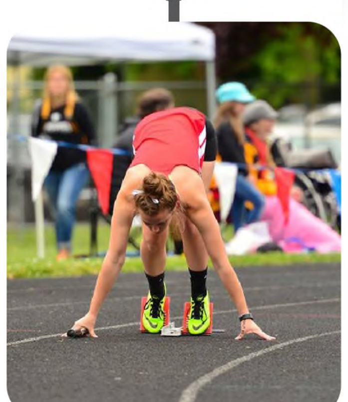
WHAT IT'S ALL ABOUT

GABI LORENZO



MECHANICAL ENGINEER & SPORTS PRODUCT DESIGNER

I AM ENERGIZED BY SOLVING COMPLEX PROBLEMS.



I BELIEVE THAT GREAT DESIGN CAN ALWAYS BE IMPROVED.

FUNDING SOURCE

Wu Tsai Human Performance Alliance

HOW CAN WE HELP FEMALE DISTANCE RUNNERS REACH THEIR PEAK PERFORMANCE USING SENSOR-EQUIPPED FOOTWEAR?

REAL-TIME FEEDBACK OF SHEAR FORCES AT THE FOOT-SHOE INTERFACE CAN HELP THE ATHLETE CORRECT HER GAIT TO RUN FASTER & RUN LONGER

PROJECT IMPORTANCE

WHAT IS SHEAR?

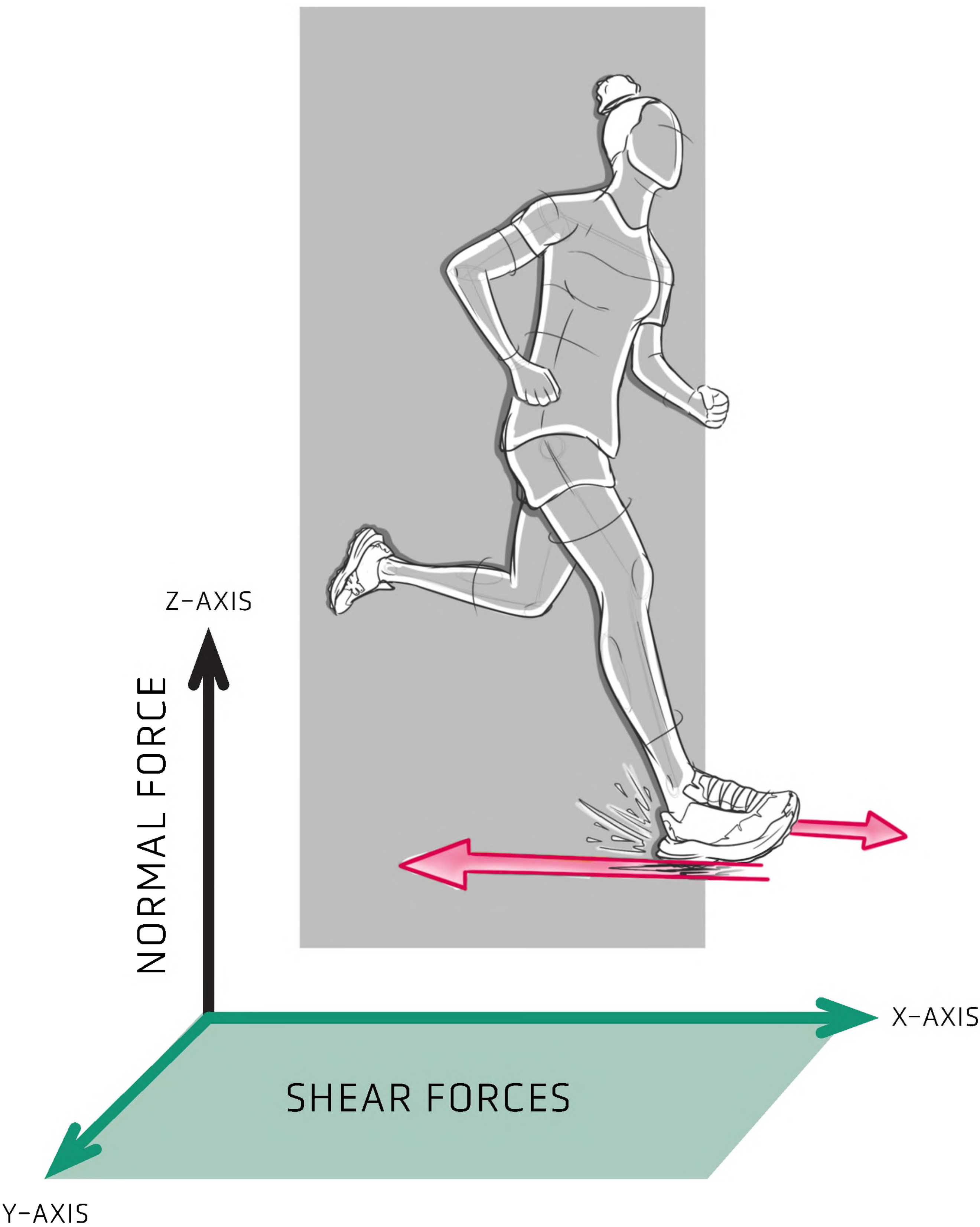
- Shear makes up 2/3 of the ground reaction forces that occur while running
- These forces allow an athlete to propel themselves forward, brake, or change direction; without shear, we could only jump upwards

IS SHEAR NEW?

- Measuring shear stress at the foot-shoe interface is extremely difficult & has not been done before
- Currently, only normal forces can be easily measured (1/3 of the forces that occur)

BENEFITS OF MEASURING SHEAR

- Understanding how shear changes throughout a run will provide opportunities to improve performance efficiencies & biomechanics


Z-AXIS
NORMAL FORCE
X-AXIS
SHEAR FORCES
Y-AXIS

ATHLETE & ENVIRONMENT

FEMALE DISTANCE RUNNERS

- 20 to 35 years old
- Specializing in 10k to marathon distances

ELITE ATHLETES

- Women who run at a high level & strive for constant improvement
- Athletes who trust technology

SPRING IN PORTLAND, OREGON

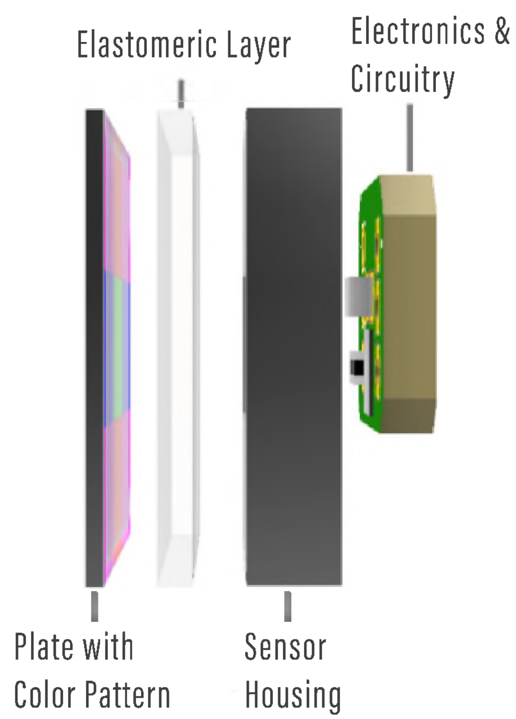
- Designed for unpredictable precipitation & slick surfaces

ROAD & TRAIL

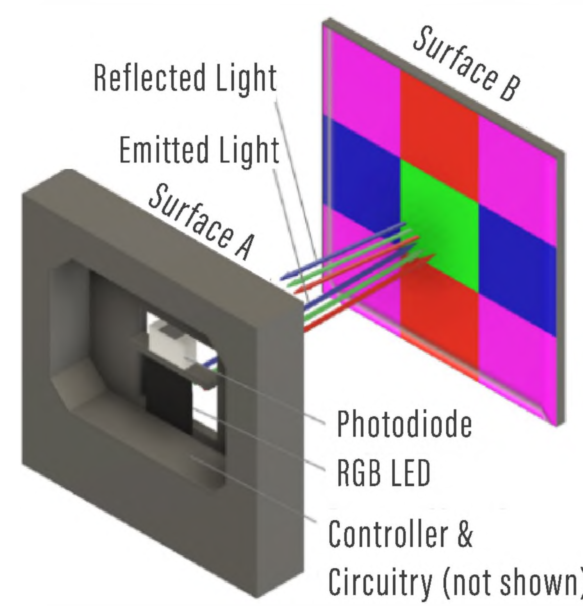
- Two versions for however she wants to train

THE SENSOR

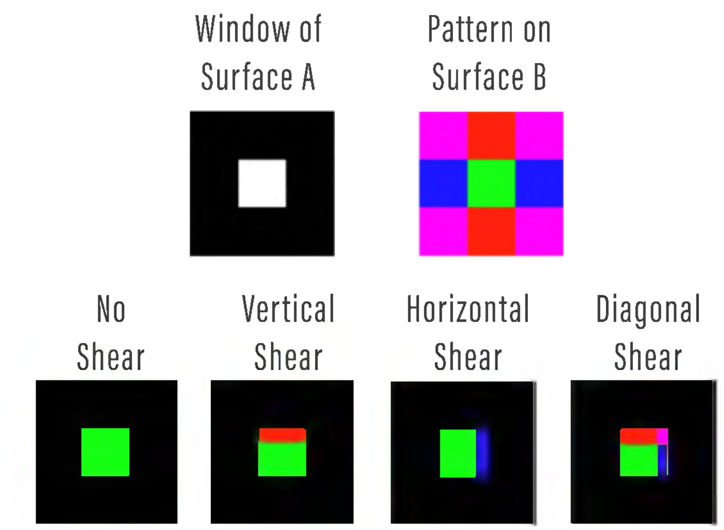
SENSOR ARCHITECTURE



SENSOR FUNCTION



VISUALIZATION OF SHEARING



SENSOR CONSTRAINTS

- PLANE OF ZERO DISPLACEMENT TO MEASURE DISPLACEMENT FROM
- SENSOR IS RIGID BUT NEEDS TO BE IMPERCEPTIBLY INTEGRATED INTO A DEFORMABLE BODY
- DEFORMABLE BODY NEEDS TO SHIFT ACROSS THE COLOR PATTERN

DEVELOPMENT TEAM

BIOMECHANICS
BOWERMAN SPORTS SCIENCE CENTER

MIKE HAHN

BIOMECH. & ENGR.
BSSC & KNIGHT CAMPUS

MICHAEL MCGEEHAN

ELECTRICAL ENGINEERING
KNIGHT CAMPUS

GHEE KEAT ONG

AREAS OF INNOVATION

TAU-TECH

- Sensor that accurately measures multi-axial shear stress at the foot-shoe interface
- Records real-time feedback via Bluetooth to an app

IMPULSE INTEGRATION SYSTEM

- Sole unit construction that imperceptibly integrates the sensor with no plantar pressure hot spots
- Provides high-energy return with dialed-in flexibility & impact attenuation

ACTIVO-ARCH

- Medial cage designed to provide the athlete with the perception of support & increase lockdown on declines
- Arch activiation & support is especially important for female athletes

TOTALIS TRACTION

- Trail & road traction patterns that provide confident grip in wet conditions

RESEARCH

TESTING BENCHMARK PRODUCTS

BENCHMARK PRODUCTS

TORIN IQ $220

ALTRA, MEN'S 7

- Collects data on impact force & location, contact time, & cadence to improve efficiency
- Interfaces with an app via Bluetooth for on-the-run feedback with live coaching
- Replaceable internal battery for usability
- The first commercially-available "smart shoes" released in 2017, no longer available from Altra

PEGASUS TRAIL 3 $160

NIKE, WOMEN'S 8

- Gore-Tex layer to keep water out & feet dry
- Dynamic fit band system through the midfoot for secure support & lockdown
- Increased traction at the heel & toe for grip going uphill or downhill
- Nike React tech is lightweight & durable while offering a smooth, responsive ride

PEGASUS 38 $120

NIKE, WOMEN'S 8

- Mid-level cushion for tons of energy return & comfort on runs of any length
- Mesh upper for ultimate breathability
- Air Zoom unit at the forefoot to create a responsive bounce
- Comfortable midfoot webbing to keep the foot snug & secure throughout the gait cycle

SWOT ANALYSIS

	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
UPPER	- Soft sandwich mesh with thick, looped eyelets that provide great lockdown without hot spots - **Conforms well to the foot & provides stability** - Gusseted tongue for better lockdown - Non-slip laces with improved lock down through throat geometry	- **Plush tongue padding & sandwich mesh trap heat & sweat** - Sometimes fit is too narrow which doesn't work well for wider feet; other times fit is too wide which doesn't provide proper lockdown - Toe box volume is often too big or too small	- **Reduce the layering of the upper to create better ventilation & breathability** - Potentially apply a DWR finish as spring is often a wet season (but this may not be needed as this is for summer as well)	- Reducing the layering of the upper will most likely reduce the comfort & stability of the upper - DWR finish is probably not needed and would just add cost
SOCKLINER	- Inexpensive - Fits the shoe interior well - **Deep heel cup eliminates slippage**	- Not anti-microbial or odor resistant	- Addition of anti-odor or sweat wicking technology - Insoles contoured to the unique foot morphology due to sex	- Increasing technology in the insole will increase price - Insoles are often overlooked & technology in this area is often viewed as unnecessary
MIDSOLE	- Forefoot air unit increases comfort - **Embedded S-shaped, full-length nylon plate provides comfort, impact attenuation, & solid energy return** - Rocker technology helps the foot move through the proper biomechanical gait	- Too much cushioning can slow the runner down - Requires a break-in period to be comfortable - Single density foam - **No rocker technology** - No rock or energy return plate	- Variable density cushioning to specifically cater to the individual cushioning needs for different areas of the foot - **Addition of sensor technology** - Full-length energy plate for a faster midsole	- Increasing technology in the midsole will increase price - Including a sensor may impact comfort and will increase weight
OUTSOLE	- Made of hard-wearing, durable rubber that resists abrasion - **Visually-pleasing outsole design** - **Decent traction performance** - Lightweight design	- **Traction is below average on wet surfaces due to the hard rubber outsole material** - Outsole doesn't fully protect the foam midsole which can cause damage to the foam when running on a road that has debris	- Redesign the outsole & traction pattern to provide better grip on wet surfaces - **Develop a full-length traction pattern that is designed specifically for heel-strikers**	- Creating an outsole designed specifically for wet surfaces may impact the performance of the outsole on dry surfaces as well as the durability of the outsole - A full-length traction pattern may add unnecessary weight

"FUNCTIONAL COMFORT"

THE FOOTWEAR NEEDS TO INTEGRATE A SHEAR SENSOR *WITHOUT COMPROMISING UNDERFOOT COMFORT*

OVERALL WEIGHT OF THE SHOE
- Increasing the weight of a shoe will affect running efficiency & decrease performance [100g+ slows down athlete by 1%]

DUROMETER & FLEXIBILITY OF THE SOLE UNIT
- If the sensor does not allow the sole unit to flex with a similar amount of force, then this will negatively affect performance

PLANTAR PRESSURE DISTRIBUTION
- Plantar pressure hot spots originating adjacent to or at sensor placement will affect comfort

OUTSOLE TRACTION
- Outsole traction is key to helping the athlete feel confident & comfortable in the footwear

WEIGHT

DATA COLLECTION

1 INSPECT THE SHOE

- Shoe is clean; insole & laces are present

2 WEIGH THE SHOE

- Zero the scale; place the shoe on the scale

WEIGHT RESULTS

		
244 GRAMS	259 GRAMS	245 GRAMS

DUROMETER

DATA COLLECTION

1 PREP THE DUROMETER

- Press indentor on surface 20 times

2 TAKE THE MEASUREMENT

- Select a flat surface
- Press the indentor down perpendicularly until the presser foot touches the surfaces

3 REPEAT

- Take multiple measurements for each midsole
- Take multiple measurements for each outsole

MIDSOLE RESULTS

		
31.8 SHORE A	29.1 SHORE A	31.8 SHORE A

OUTSOLE RESULTS

		
61.0 SHORE A	67.3 SHORE A	62.0 SHORE A

SOLE UNIT FLEXIBILITY

DATA COLLECTION

1 CLAMP THE SHOE DOWN

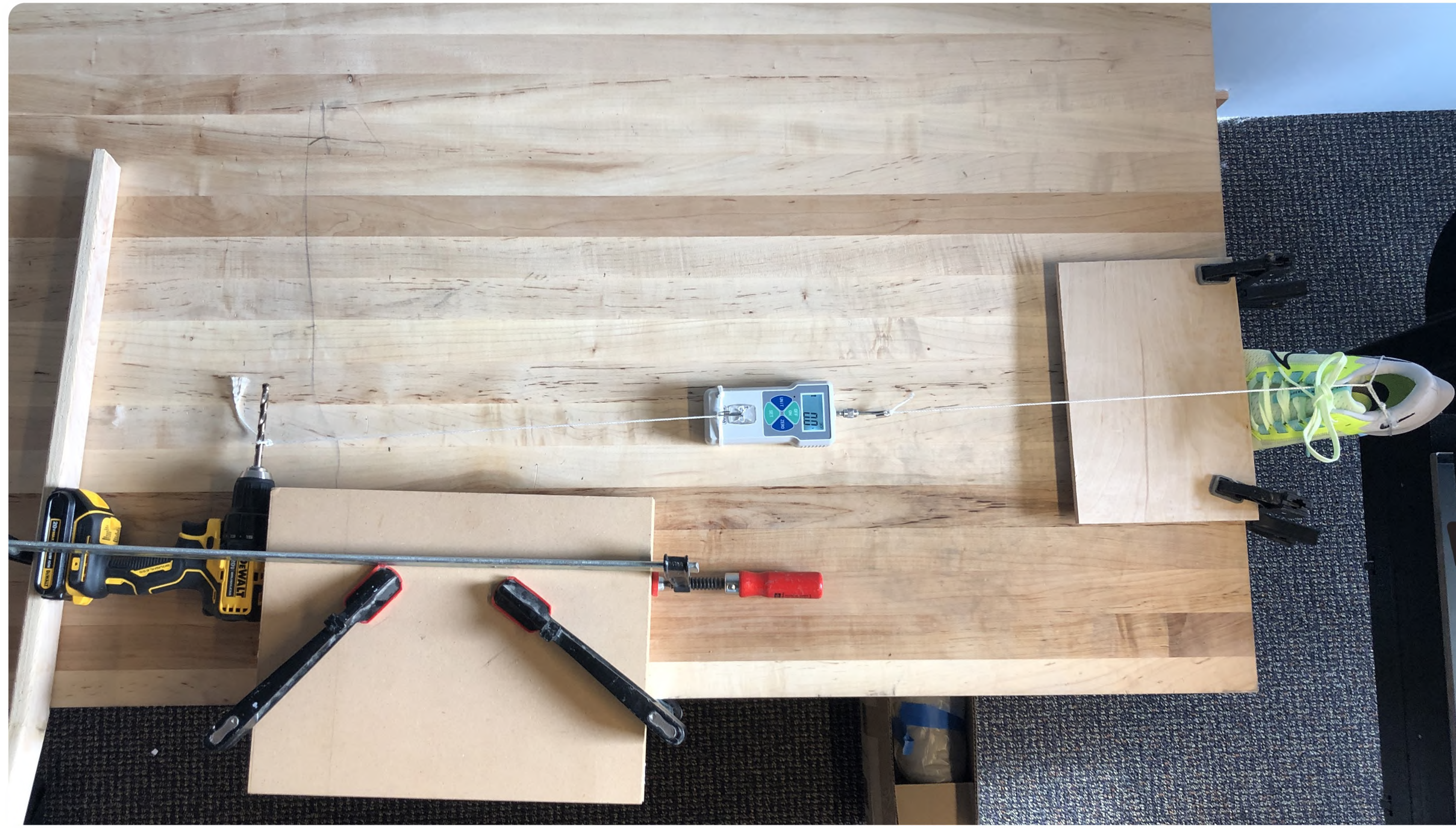
- Clamp at forefoort breaking point of shoe
- Set force gauge to measure peak force

2 APPLY FORCE TO FLEX

- Use drill to pull heel to 90 degrees flexion
- Use drill at a controlled speed
- Ensure that force gauge stays in place

3 REPEAT & RECORD

- Record the peak force in Newtons
- Repeat 5 times for each shoe (R & L)



TORIN IQ RESULTS	PEGASUS TRAIL 3 RESULTS	PEGASUS 38 RESULTS
 **35.6** NEWTONS	 **30.0** NEWTONS	 **29.0** NEWTONS

PLANTAR PRESSURE

DATA COLLECTION

1 PLACE ARION INSOLES

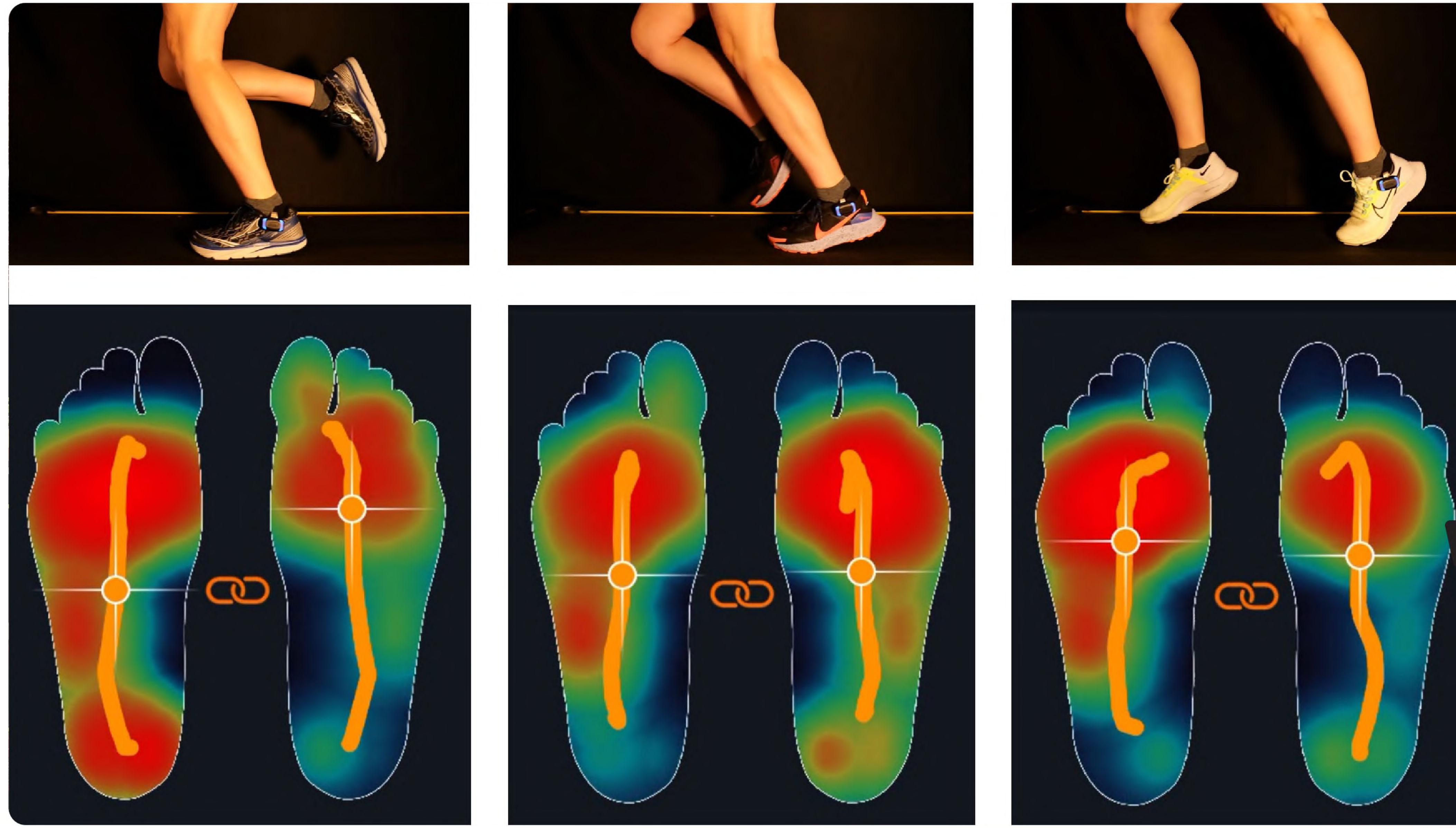
- Put insoles in shoe & shoes on athletes
- Make sure app & insoles are functioning

2 TREADMILL RUN

- Use app to record a 5 minute treadmill run
- Ask athletes questions regarding comfort at the 2.5 minute & 5 minute marks

3 REPEAT & RECORD

- Plantar pressure distribution videos & graphs
- Repeat for all test footwear



TORIN IQ IMPULSE	PEGASUS TRAIL 3 IMPULSE	PEGASUS 38 IMPULSE
 219 N*s	 210 N*s	 223 N*s

WEAR TEST PERCEPTIONS

	COMFORT	CUSHIONING	VENTILIATION	ENERGY RET.	AESTHETICS	OVERALL*
	5.6 /10	4.4 /10	6.0 /10	2.9 /10	2.5 /10	4.8 /10
	7.7 /10	6.2 /10	5.8 /10	6.4 /10	7.4 /10	7.0 /10
	7.3 /10	7.8 /10	5.4 /10	7.5 /10	6.6 /10	6.9 /10

OF PARTICIPANTS 05

*OVERALL RANKING IS DETERMINED BY AVERAGING THE WEAR TESTERS' RANKS OF PERCEIVED COMFORT AT BOTH 2.5 MINUTES & 5 MINUTES, TRACTION, CUSHIONING, STABILITY, BREATHABILITY, ENERGY RETURN, FIT, & AESTHETICS.

TRACTION

DATA COLLECTION

1 PLACE WEIGHTS

- Put 4 flat weight plates inside the shoe
- 2 weights at forefoot, 2 in the heel area

2 SET FORCE GAUGE

- Use drill to pull shoe across the surface
- Use drill at a controlled speed
- Ensure that force gauge stays in place

3 REPEAT & RECORD

- Record the peak force
- Repeat for all test footwear

CONCRETE

ASPHALT

WET DIRT

CONCRETE RESULTS

		
12.1 NEWTONS	12.7 NEWTONS	12.5 NEWTONS

ASPHALT RESULTS

		
12.0 NEWTONS	12.9 NEWTONS	12.5 NEWTONS

WET DIRT RESULTS

		
13.4 NEWTONS	15.8 NEWTONS	13.5 NEWTONS

IMPROVING PERFORMANCE

“FUNCTIONAL COMFORT”

THE FOOTWEAR NEEDS TO INTEGRATE A SHEAR SENSOR **WITHOUT COMPROMISING UNDERFOOT COMFORT**

AVG. RANKING	*COMFORT*	*AESTHETICS*	*OVERALL**
	6.8 /10	**5.5** /10	**6.2** /10
	<5% ACCEPTABLE PERCENT DIFFERENCE -	>5% ACCEPTABLE PERCENT DIFFERENCE +	<5% ACCEPTABLE PERCENT DIFFERENCE -

AVG. BASELINE RESULTS	*SHOE WEIGHT*	*SOLE DUROMETER*	*SOLE UNIT FLEXIBILITY*	*IMPULSE*	*TRACTION*
	249.3 GRAMS	**34 / 65** MID / OUTSOLE SHORE A	**31.5** NEWTONS	**217.0** N*S	**13.0** NEWTONS
	<5% ACCEPTABLE % DIFFERENCE +/-	<3% ACCEPTABLE % DIFFERENCE +/-	<5% ACCEPTABLE % DIFFERENCE +/-	<3% ACCEPTABLE % DIFFERENCE +/-	<5% ACCEPTABLE % DIFFERENCE +/-

USER INSIGHTS

OF PARTICIPANTS 129

83% OF PARTICIPANTS
TRACK THEIR PERFORMANCE METRICS

55% OF PARTICIPANTS ARE
INTERESTED IN A SMART TRAINING SHOE

35 MILES BY PARTICIPANTS FOR TRAINING PURPOSES
AVERAGE MILEAGE RUN PER WEEK

"RUNNERS WILL ALWAYS PRIORITIZE A SHOE'S PERFORMANCE OVER ANY SMART FEATURES"

POTENTIAL CONCERNS WITH SMART RUNNING FOOTWEAR ACCORDING TO THE PARTICIPANTS

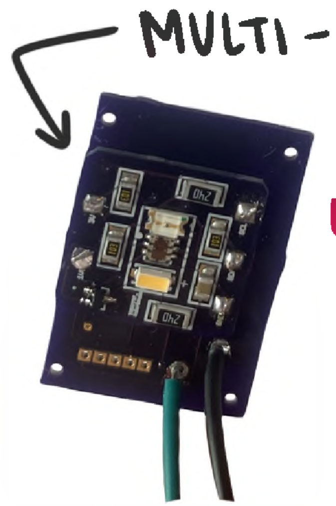
1. DECREASE IN PERFORMANCE
2. COMFORT
3. RELIABILITY
4. WEIGHT
5. PRICE
6. DURABILITY

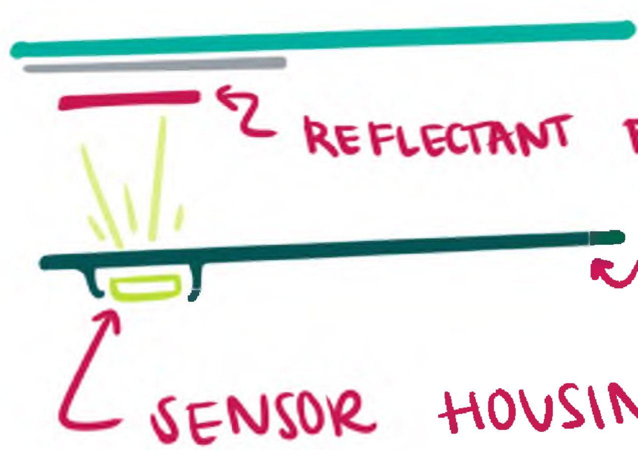
WHICH PERFORMANCE METRICS ARE MOST IMPORTANT TO RUNNERS?

IDEATION

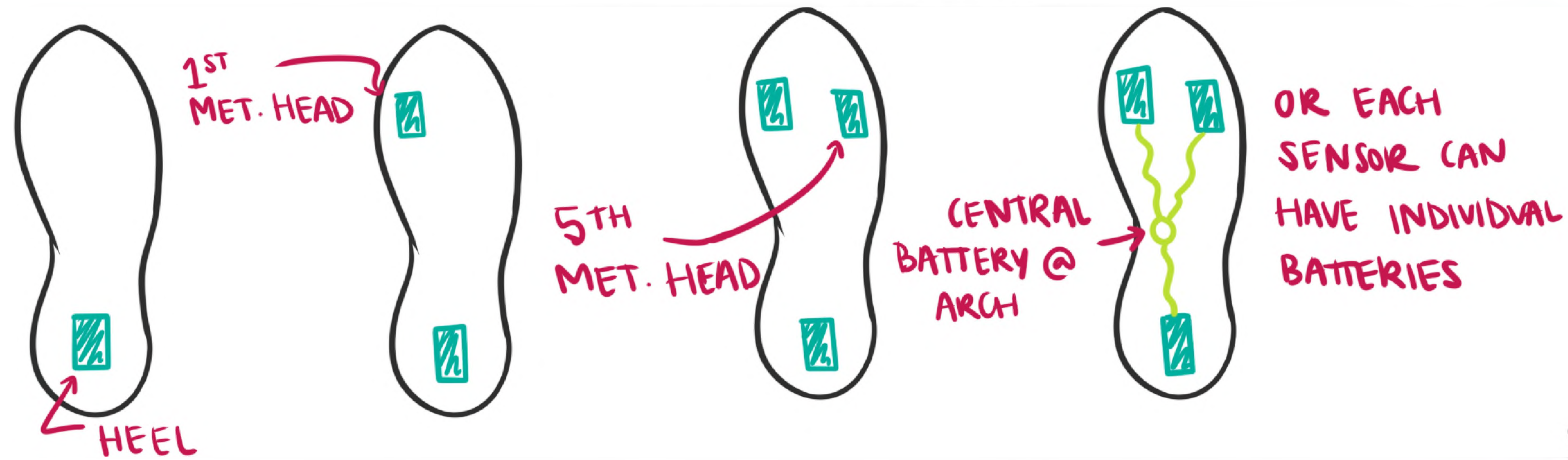
SKETCHING, PROTOTYPING, ETC.

SENSOR INTEGRATION DEVELOPMENT

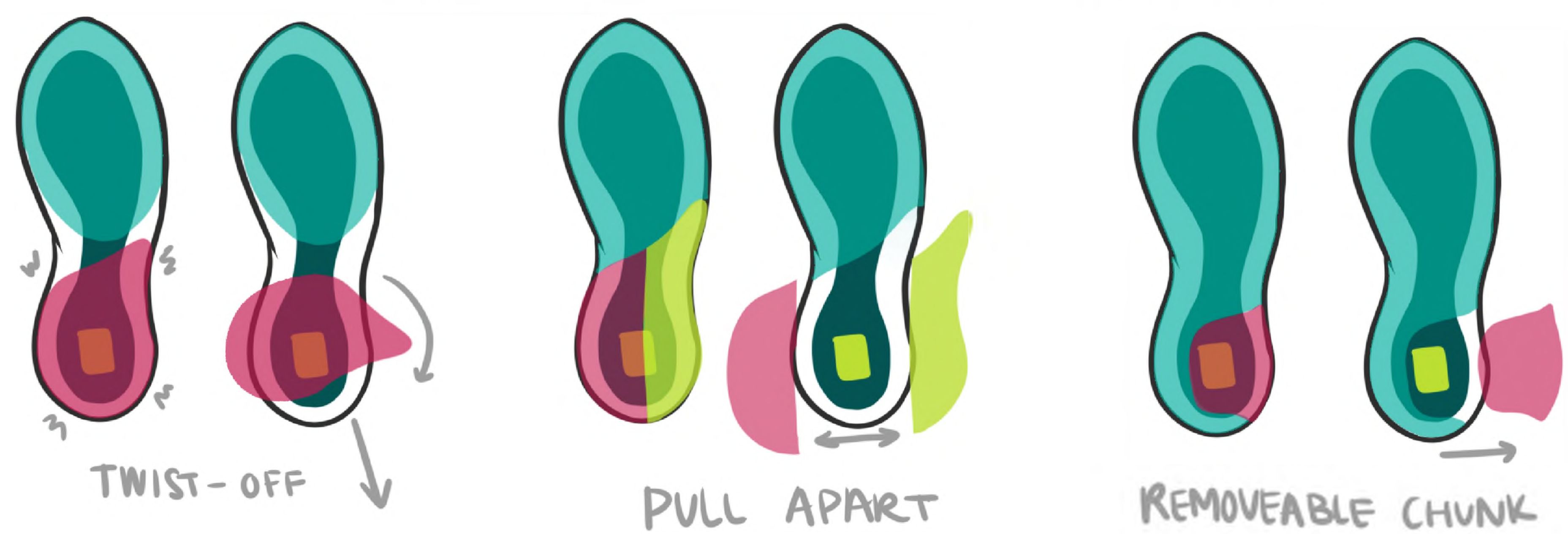




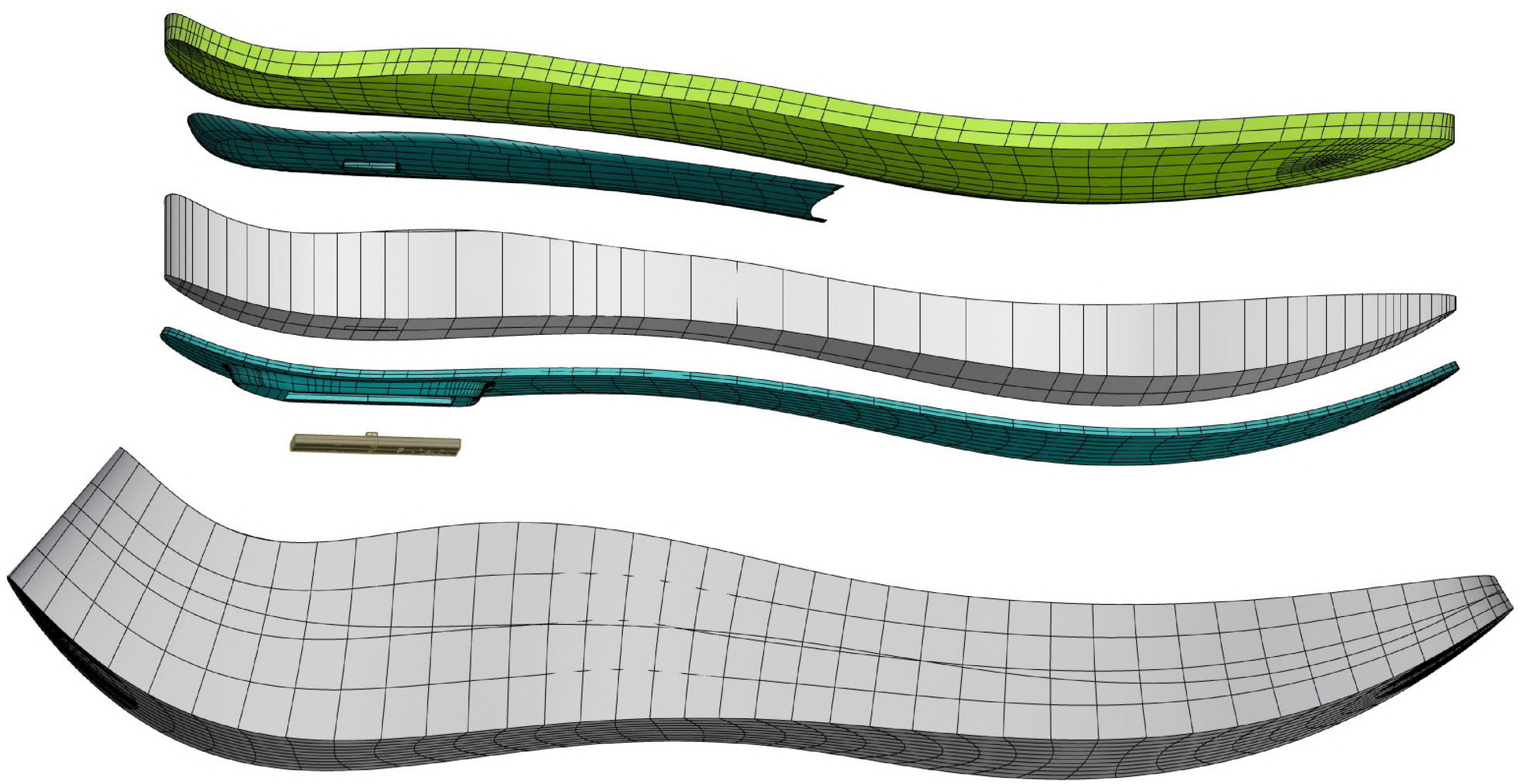
* INVESTIGATE SENSOR + BATTERY PLACEMENT

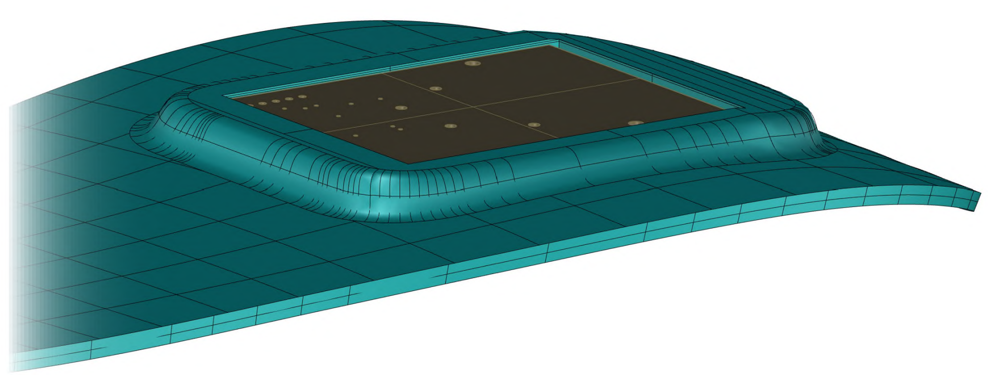


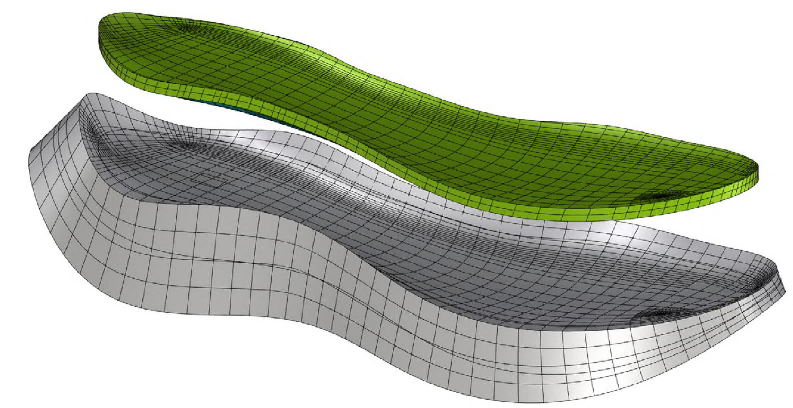
* SENSOR + BATTERY SHOULD BE ACCESSIBLE

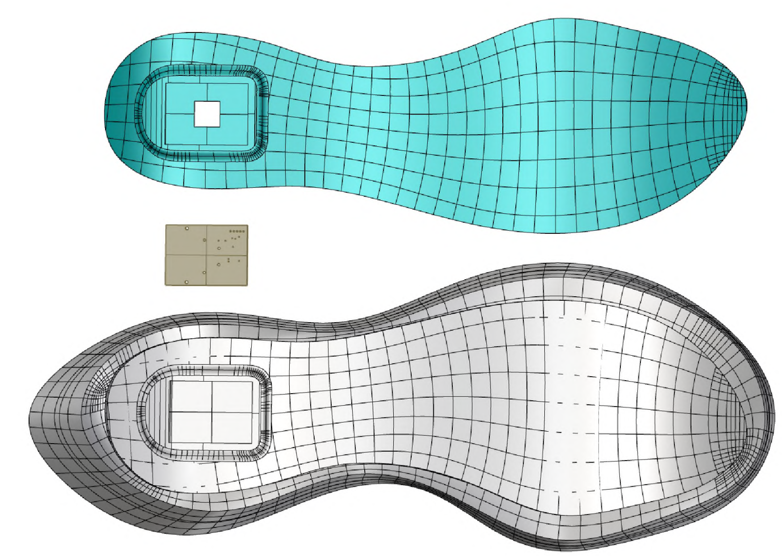


SENSOR INTEGRATION DEVELOPMENT

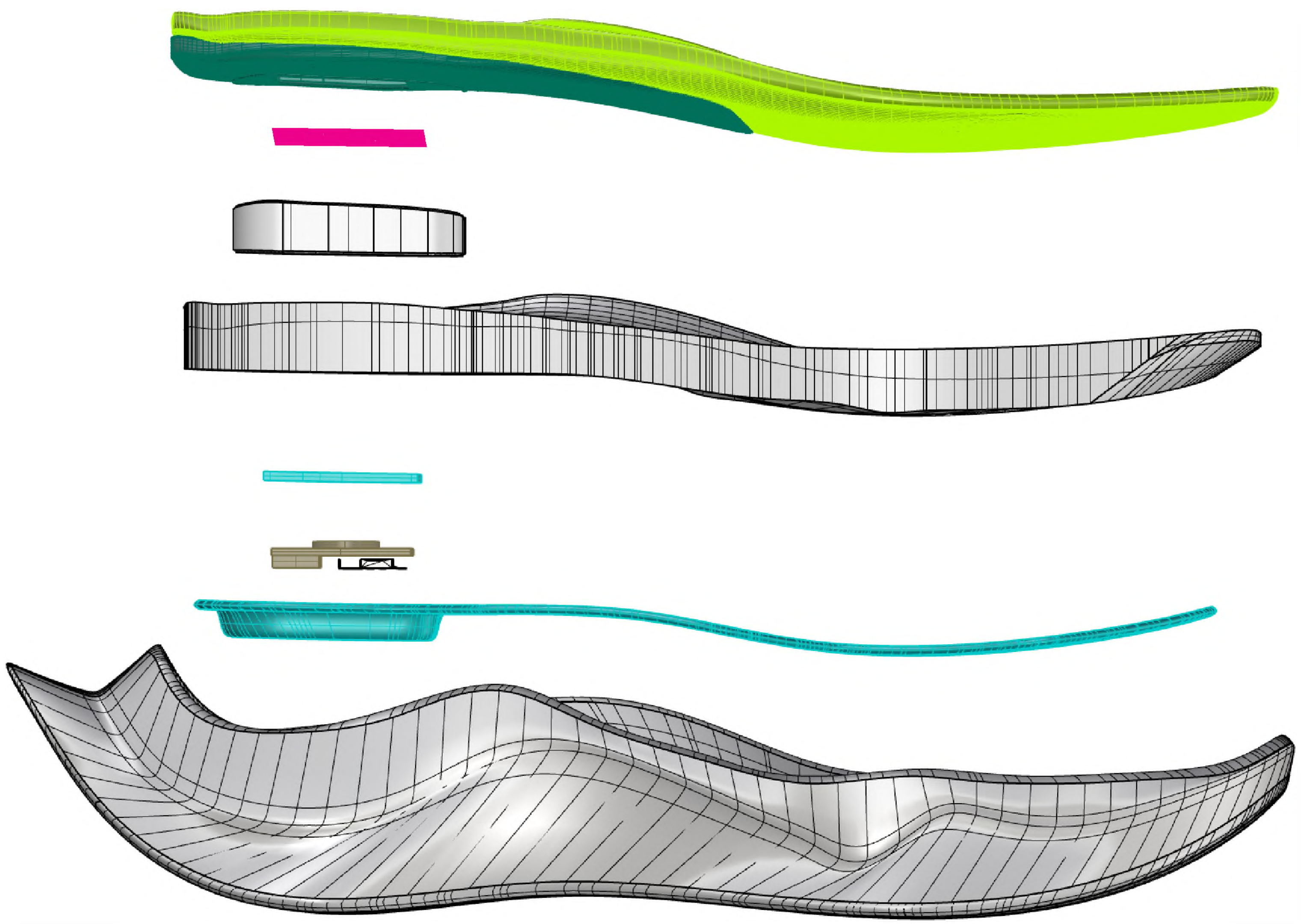


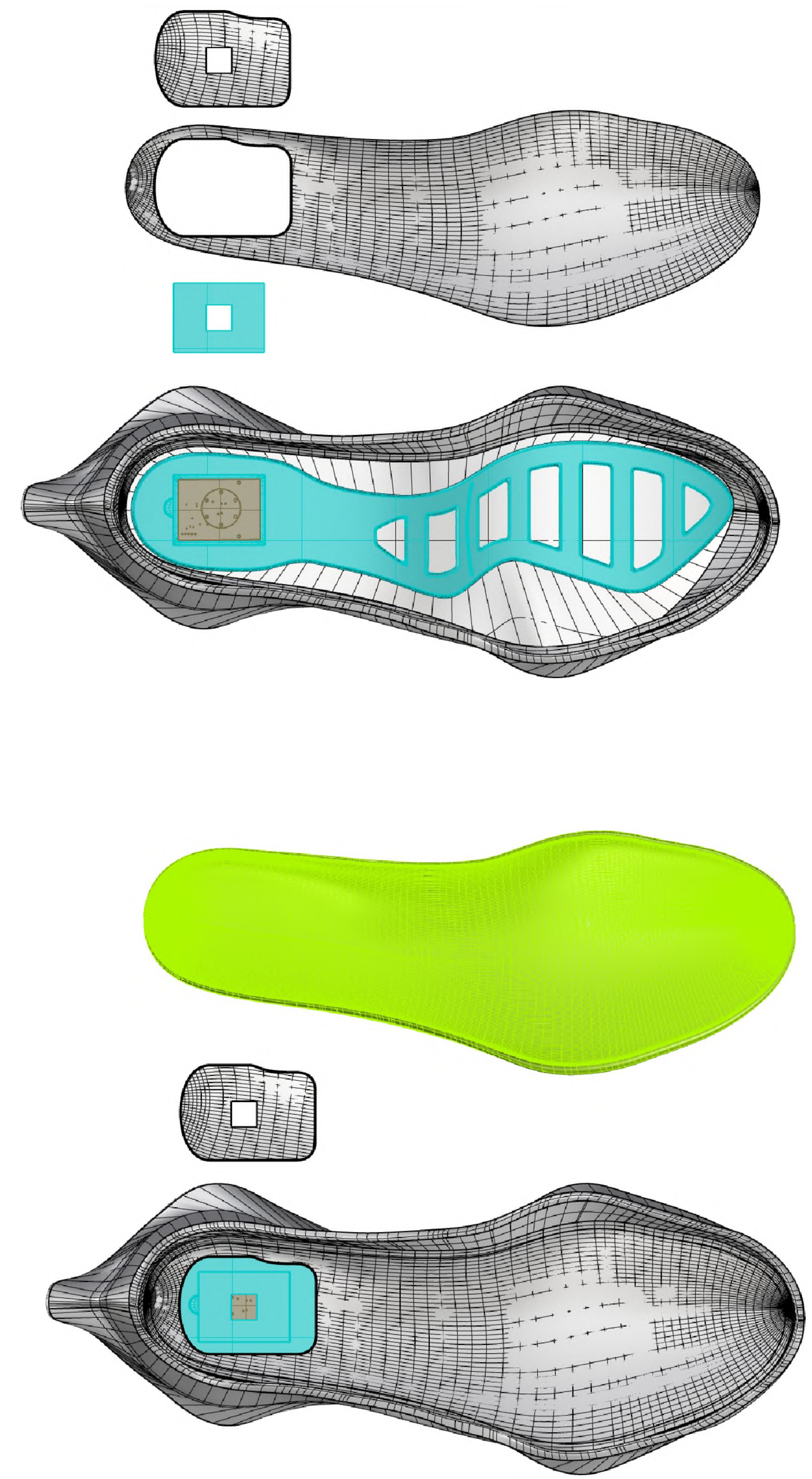




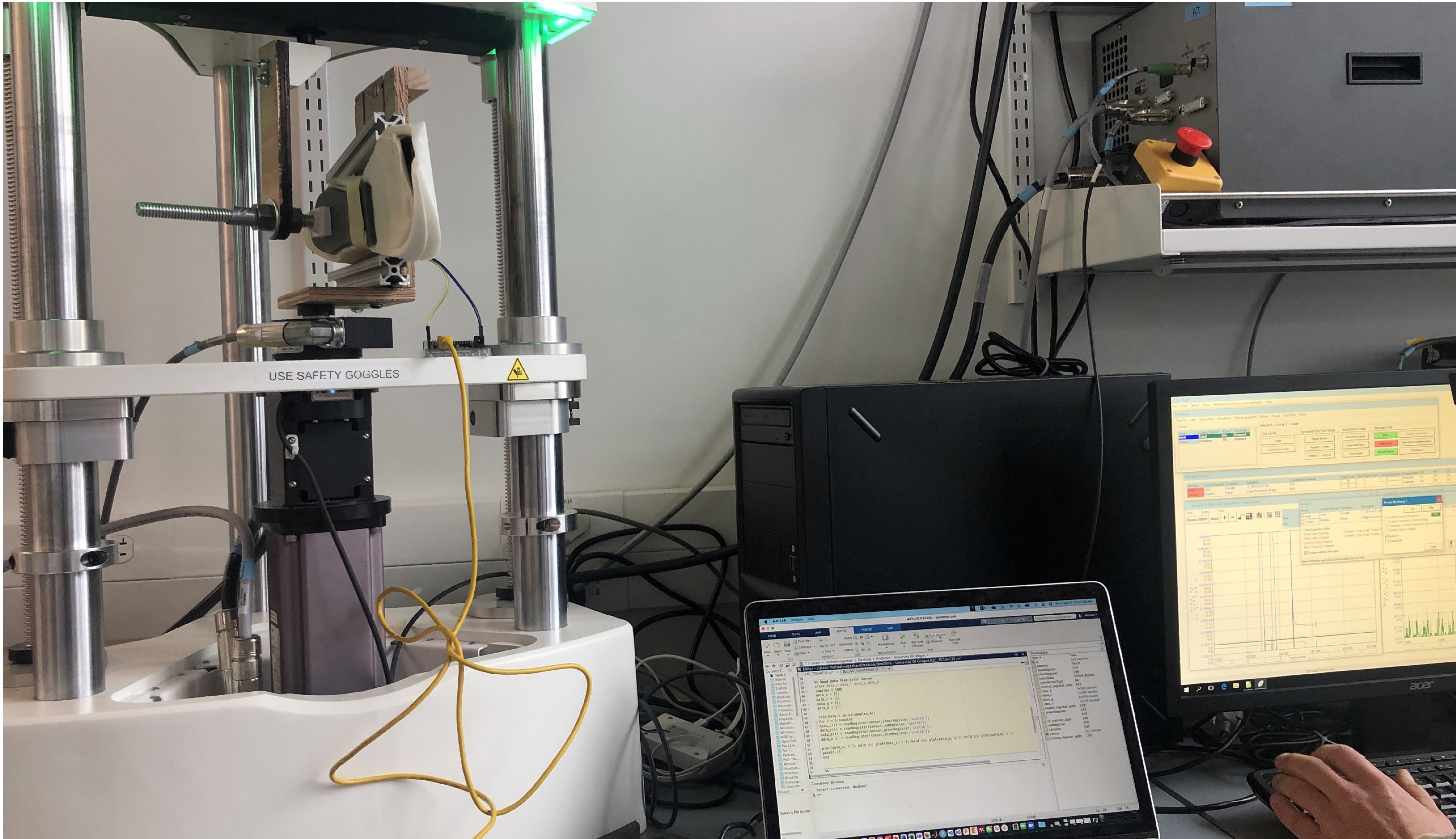


SENSOR INTEGRATION DEVELOPMENT

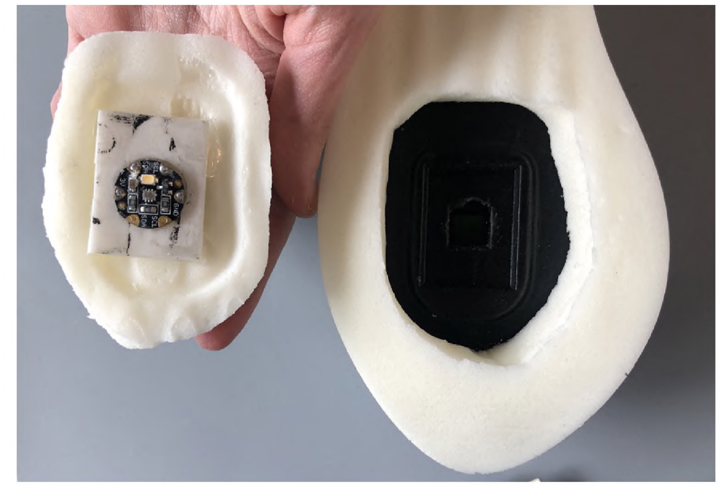




SENSOR INTEGRATION DEVELOPMENT



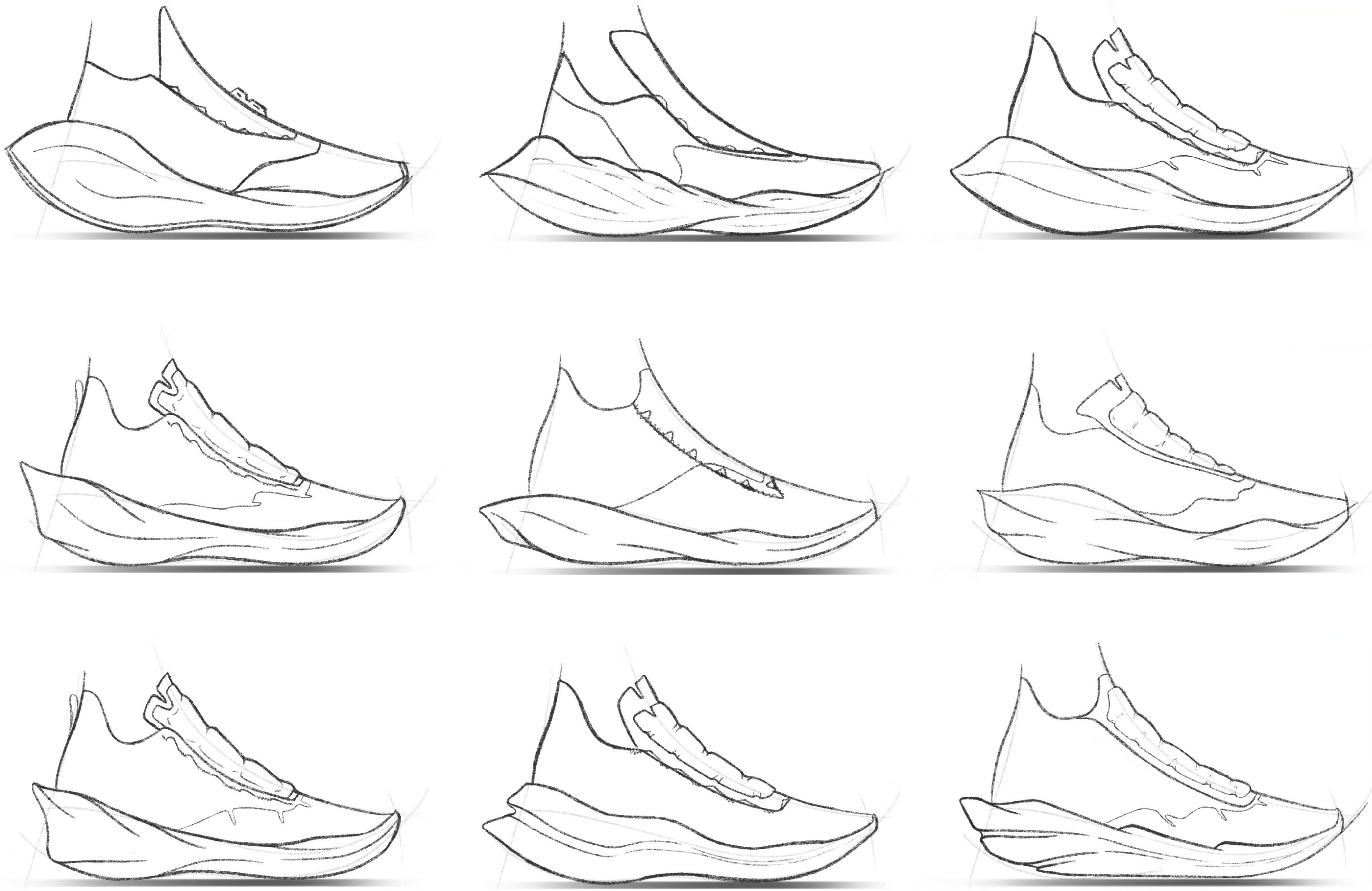
SENSOR INTEGRATION DEVELOPMENT

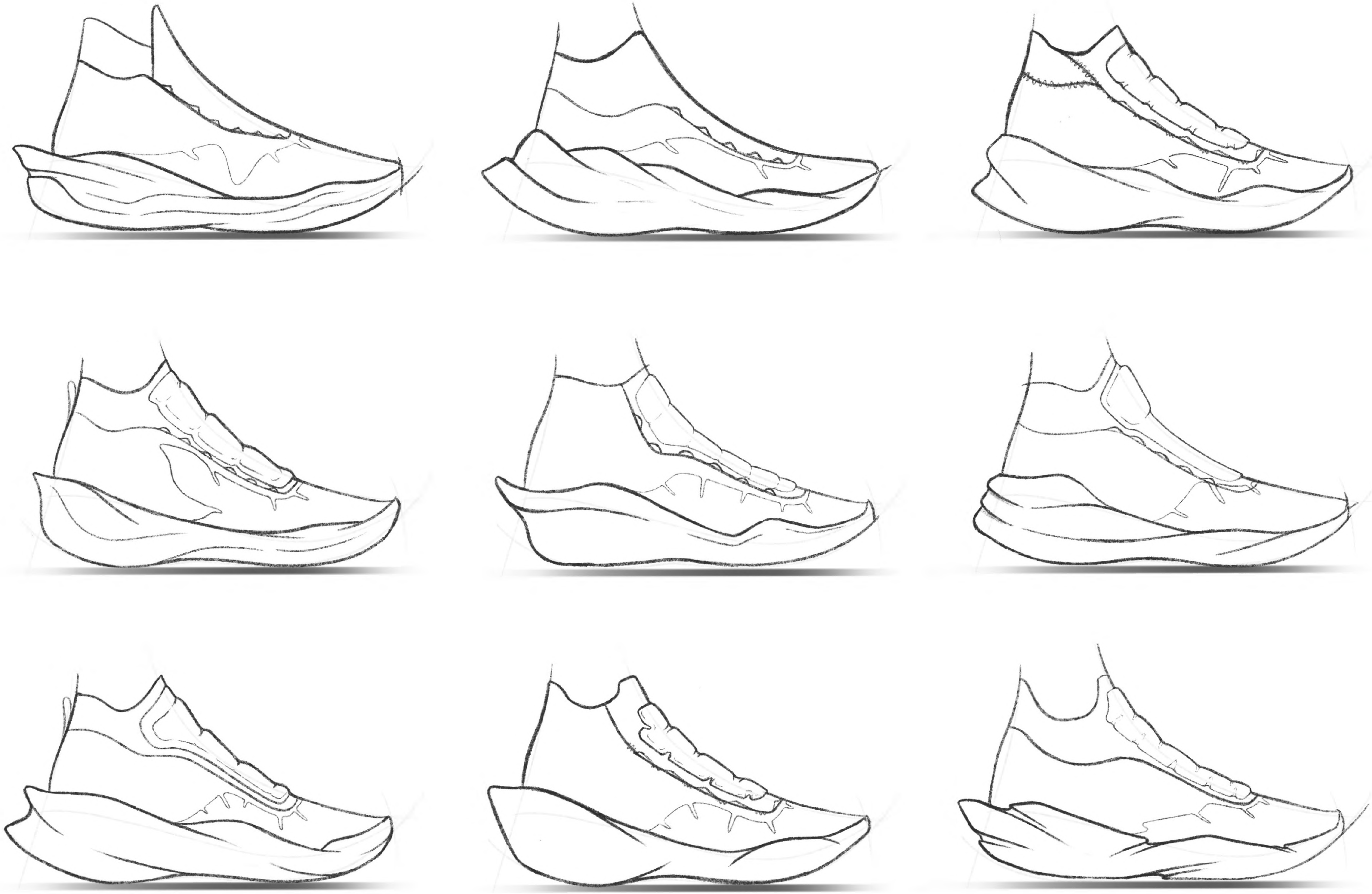


INSPIRATION & COLOR

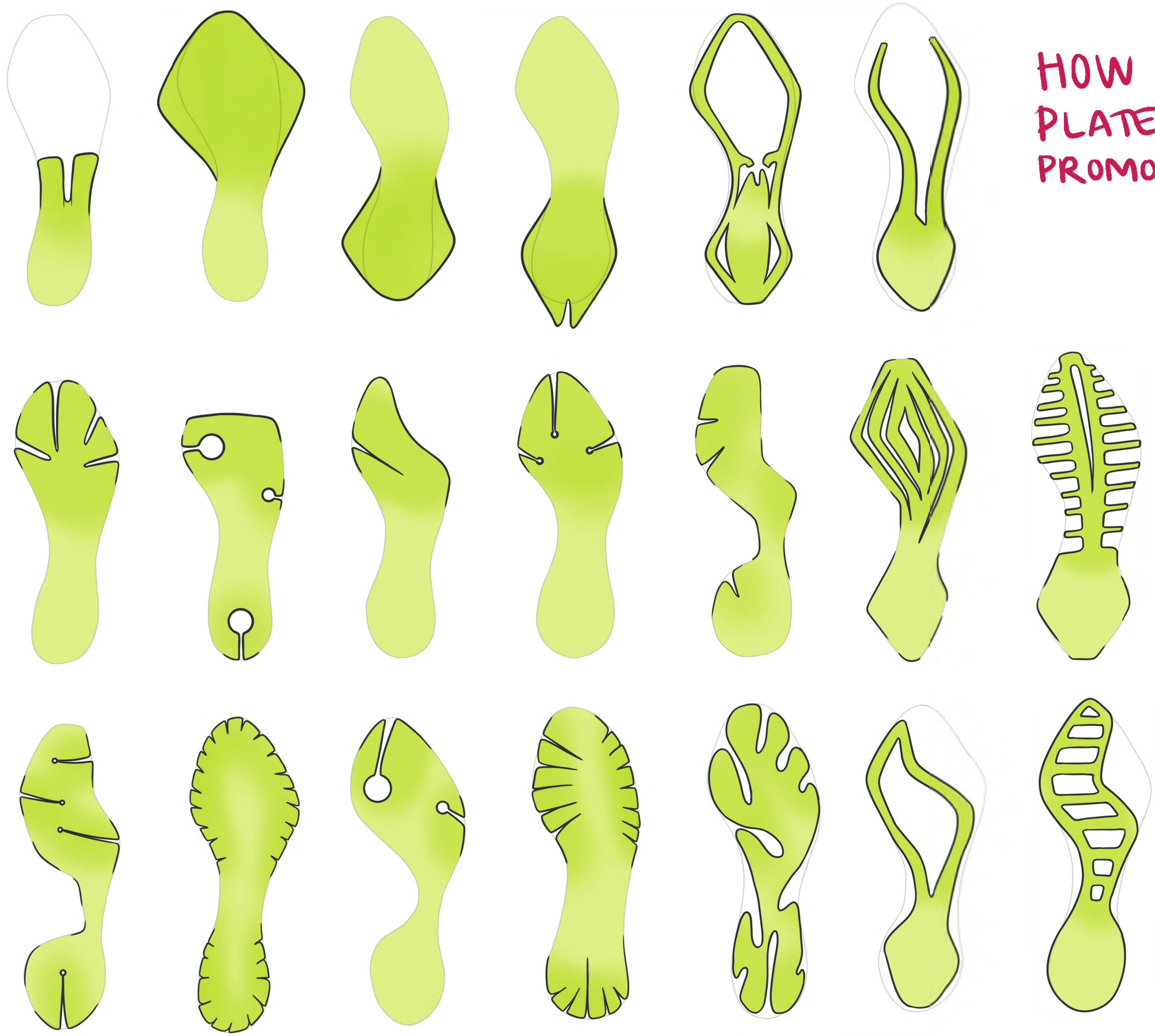
ROAD COLORWAY	
15-4305 TCX	QUARRY
12-0703 TCX	SEEDPEARL
14-0340 TCX	ACID LIME
12-0741 TCX	SUNNY LIME
18-1856 TCX	VIRTUAL PINK

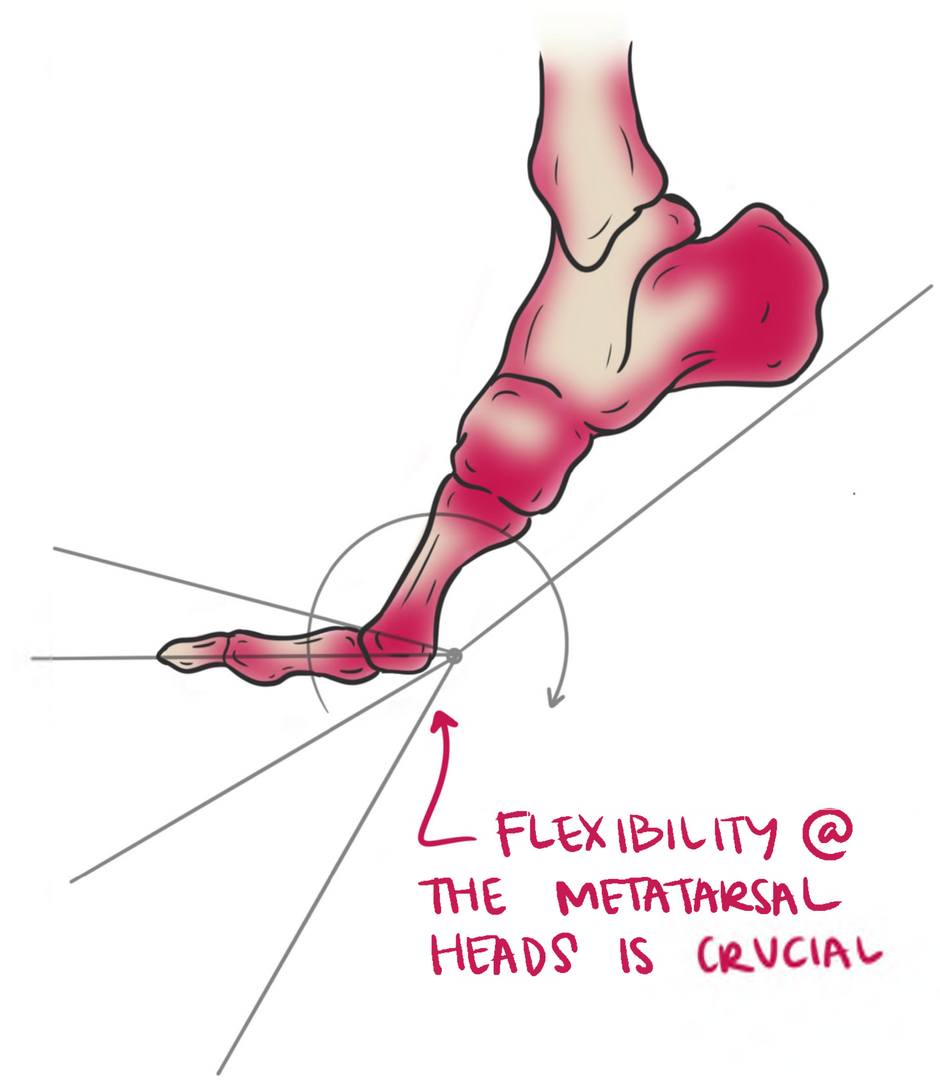
TRAIL COLORWAY	
19-4405 TCX	FOREST RIVER
15-4305 TCX	QUARRY
19-5217 TCX	STORM
16-5425 TCX	POOL GREEN
18-1856 TCX	VIRTUAL PINK



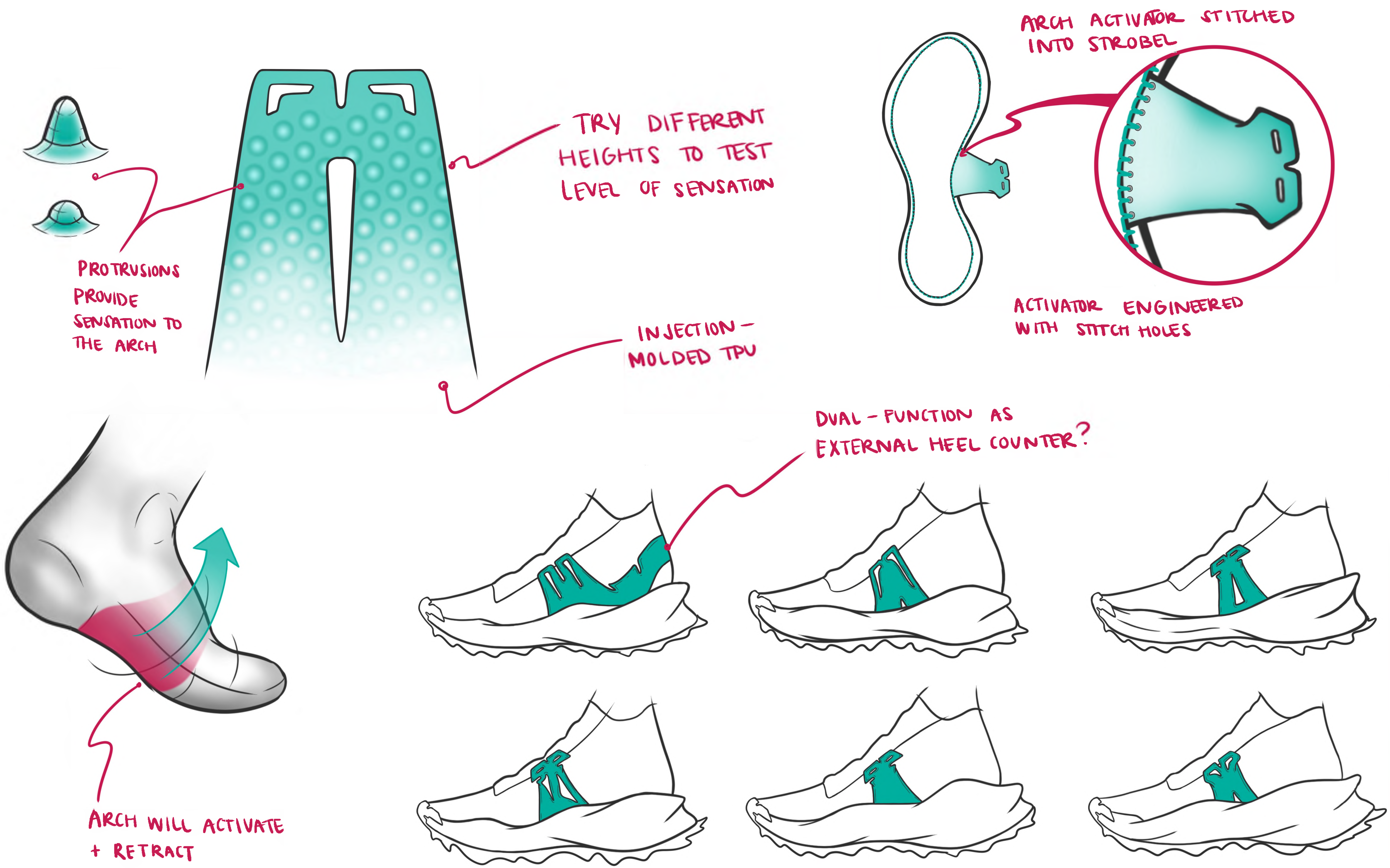


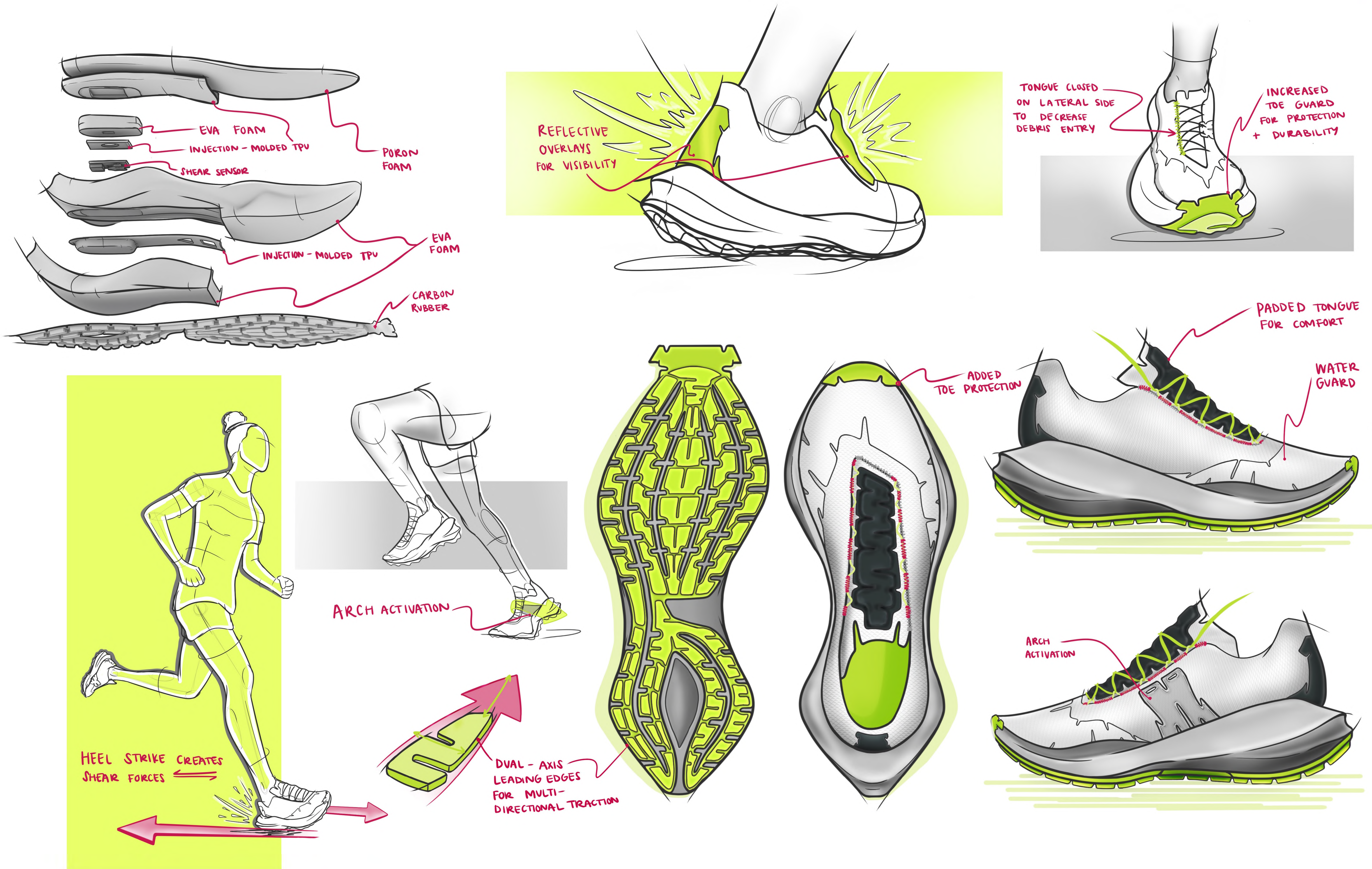
HOW CAN THE ENERGY PLATE / SENSOR HOUSING PROMOTE FLEXIBILITY?

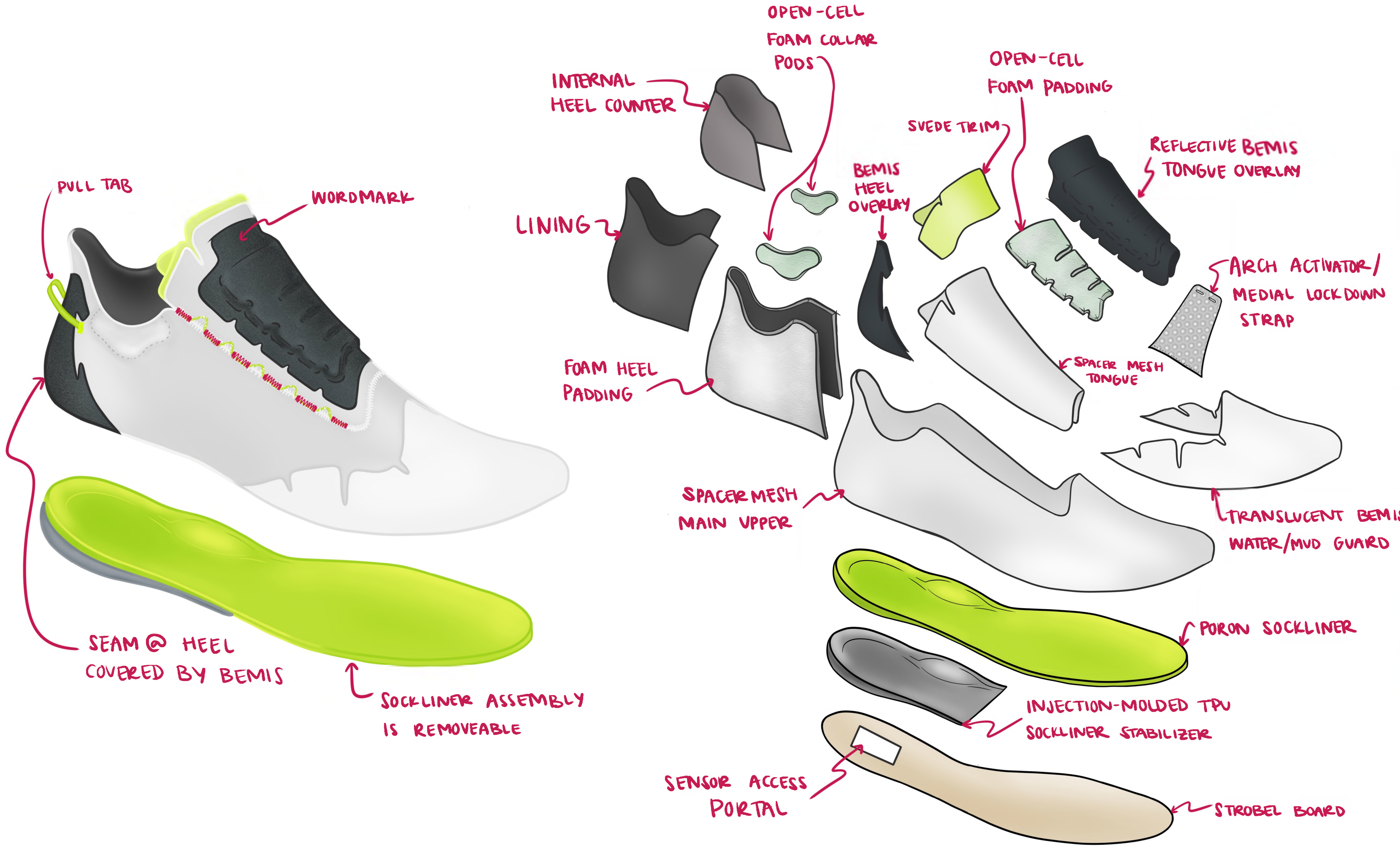


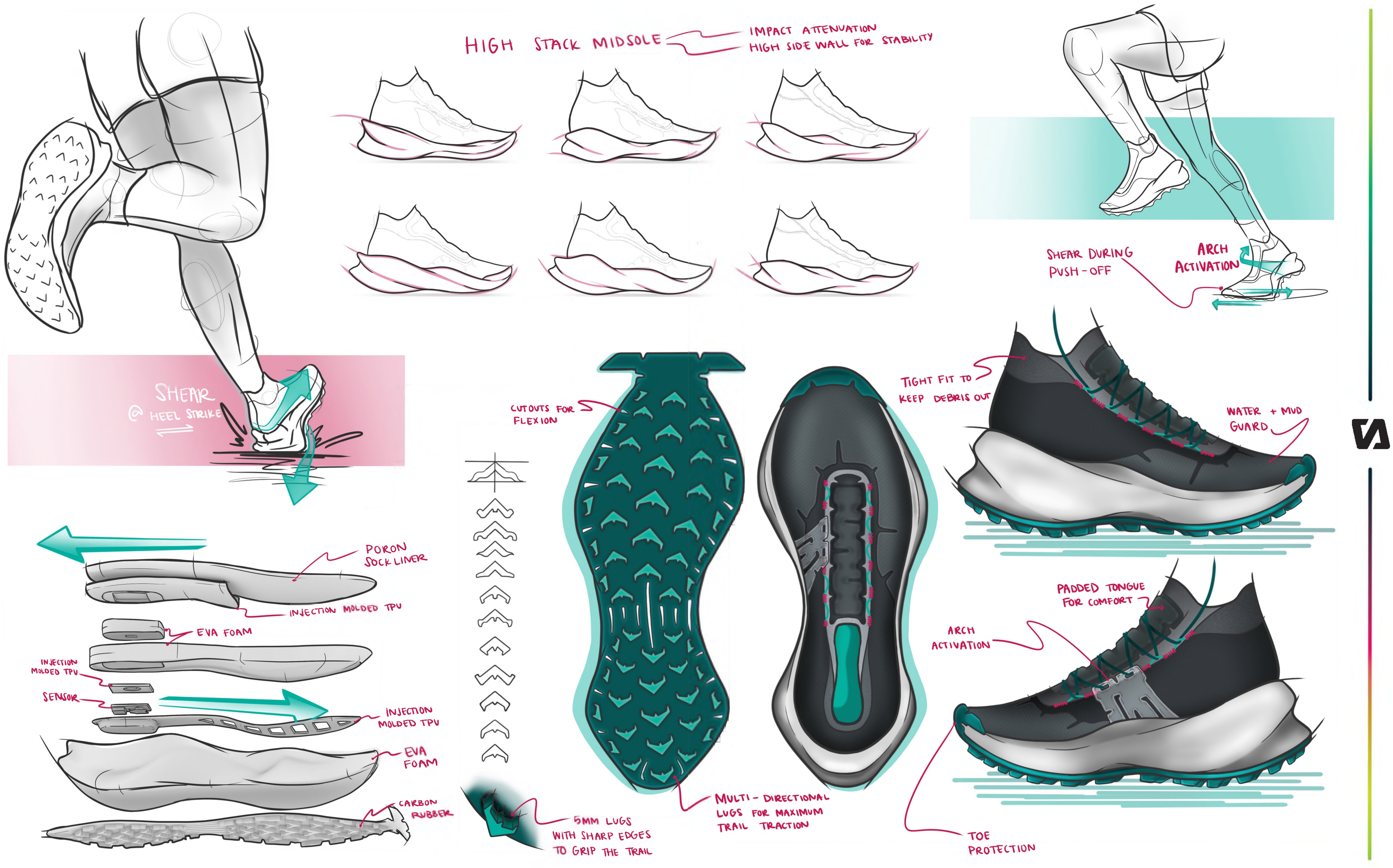


COULD BE IMPORTANT / HELPFUL TO DECOUPLE THE MEDIAL & LATERAL SIDES OF THE FOOT FOR THE TRAIL SHOE SINCE IT'S BUILT FOR VARIABLE TERRAIN

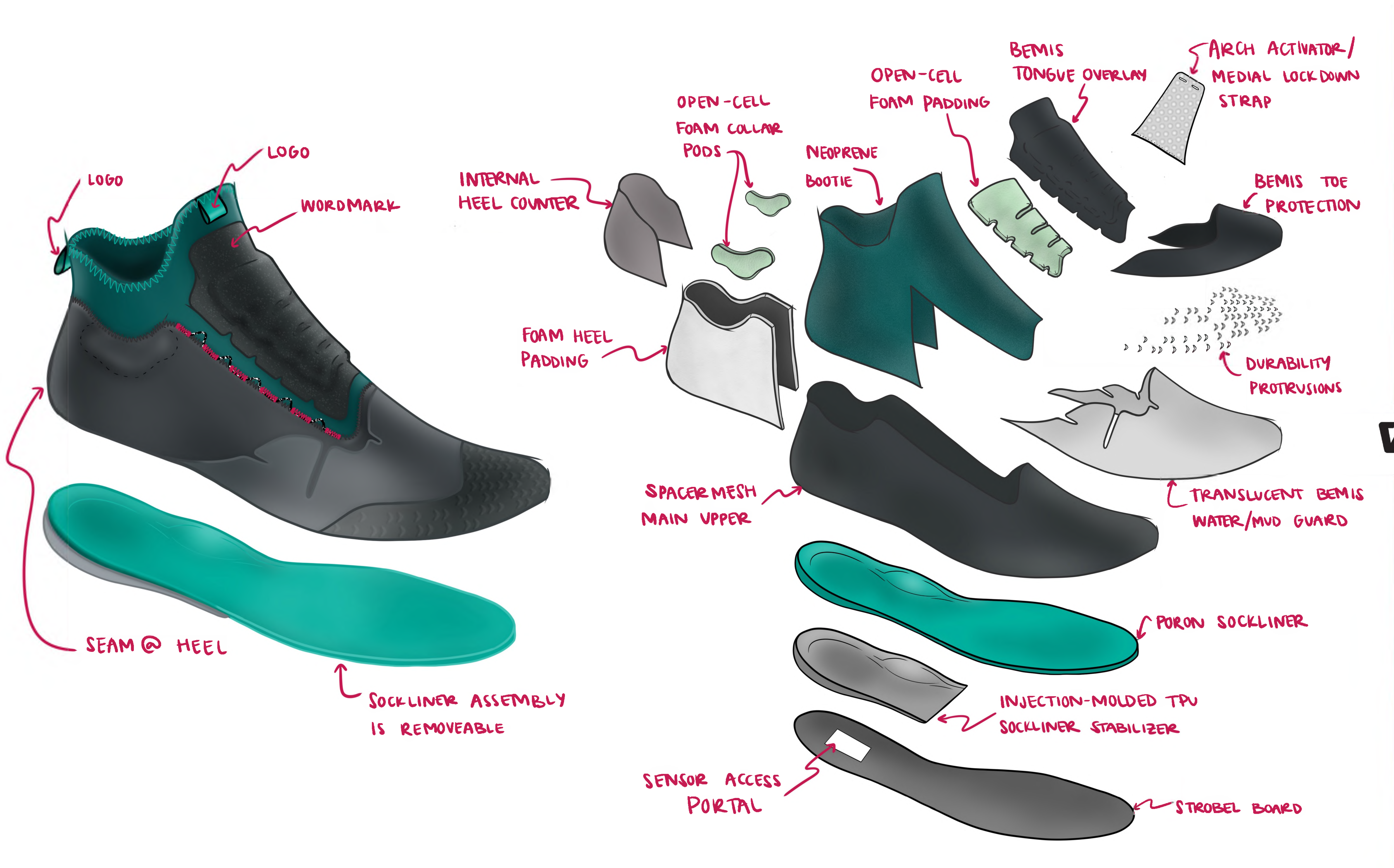

TRY DIFFERENT HEIGHTS TO TEST LEVEL OF SENSATION
PROTRUSIONS PROVIDE SENSATION TO THE ARCH
INJECTION-MOLDED TPU
ARCH ACTIVATOR STITCHED INTO STROBEL
ACTIVATOR ENGINEERED WITH STITCH HOLES
DUAL-FUNCTION AS EXTERNAL HEEL COUNTER?
ARCH WILL ACTIVATE + RETRACT


EVA FOAM
INJECTION - MOLDED TPU
SHEAR SENSOR
PORON FOAM
INJECTION - MOLDED TPU
EVA FOAM
CARBON RUBBER
REFLECTIVE OVERLAYS FOR VISIBILITY
TONGUE CLOSED ON LATERAL SIDE TO DECREASE DEBRIS ENTRY
INCREASED TOE GUARD FOR PROTECTION + DURABILITY
PADDED TONGUE FOR COMFORT
WATER GUARD
ADDED TOE PROTECTION
ARCH ACTIVATION
ARCH ACTIVATION
DUAL - AXIS LEADING EDGES FOR MULTI-DIRECTIONAL TRACTION
HEEL STRIKE CREATES SHEAR FORCES


PULL TAB
WORDMARK
SEAM @ HEEL COVERED BY BEMIS
SOCKLINER ASSEMBLY IS REMOVEABLE
INTERNAL HEEL COUNTER
OPEN-CELL FOAM COLLAR PODS
OPEN-CELL FOAM PADDING
SUEDE TRIM
BEMIS HEEL OVERLAY
REFLECTIVE BEMIS TONGUE OVERLAY
LINING
ARCH ACTIVATOR/ MEDIAL LOCKDOWN STRAP
FOAM HEEL PADDING
SPACER MESH TONGUE
SPACER MESH MAIN UPPER
TRANSLUCENT BEMIS WATER/MUD GUARD
PORON SOCKLINER
INJECTION-MOLDED TPU SOCKLINER STABILIZER
SENSOR ACCESS PORTAL
STROBEL BOARD

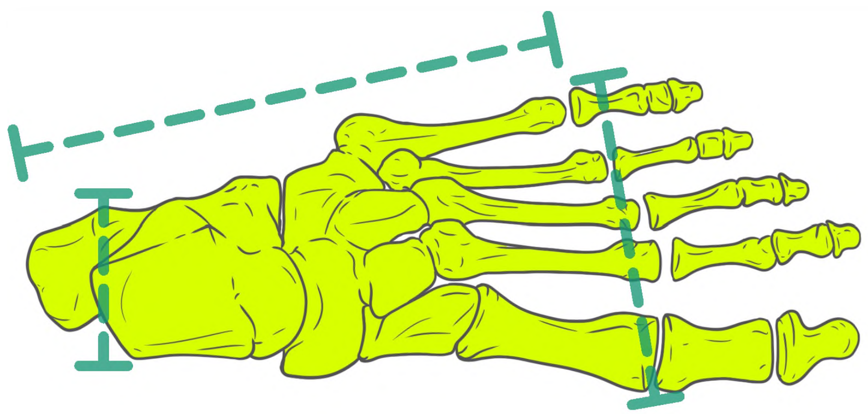


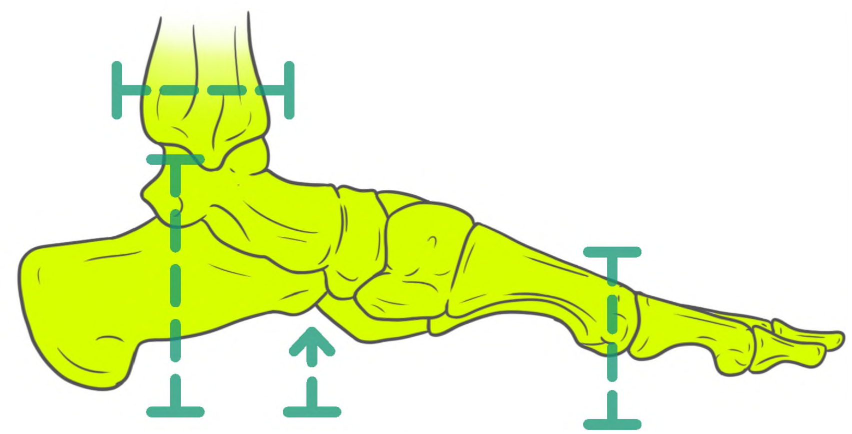
HIGH STACK MIDSOLE
IMPACT ATTENUATION
HIGH SIDE WALL FOR STABILITY
SHEAR @ HEEL STRIKE
SHEAR DURING PUSH-OFF
ARCH ACTIVATION
TIGHT FIT TO KEEP DEBRIS OUT
WATER + MUD GUARD
CUTOUTS FOR FLEXION
PORON SOCK LINER
INJECTION MOLDED TPU
EVA FOAM
INJECTION MOLDED TPU
SENSOR
INJECTION MOLDED TPU
EVA FOAM
CARBON RUBBER
5MM LUGS WITH SHARP EDGES TO GRIP THE TRAIL
MULTI-DIRECTIONAL LUGS FOR MAXIMUM TRAIL TRACTION
PADDED TONGUE FOR COMFORT
ARCH ACTIVATION
TOE PROTECTION

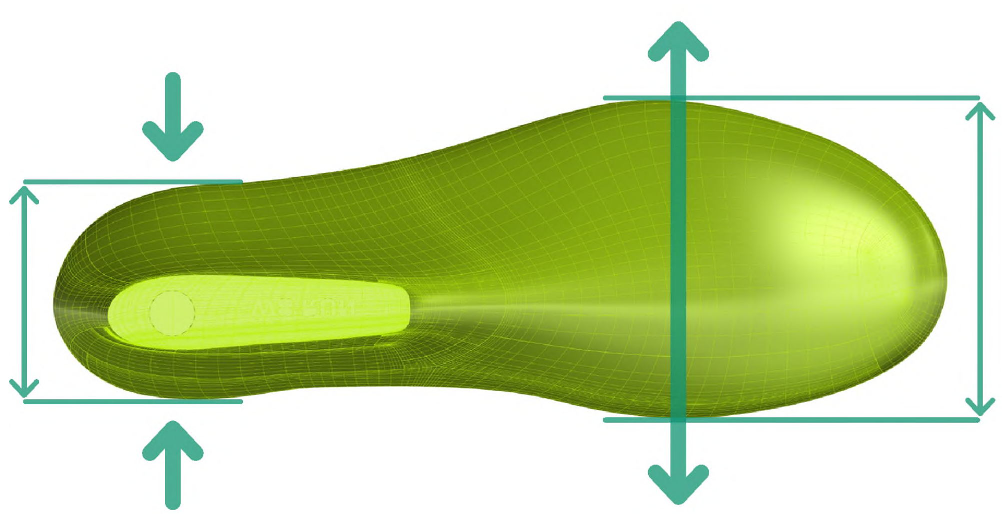

LOGO
LOGO
WORDMARK
SEAM @ HEEL
SOCKLINER ASSEMBLY IS REMOVEABLE
INTERNAL HEEL COUNTER
OPEN-CELL FOAM COLLAR PODS
FOAM HEEL PADDING
NEOPRENE BOOTIE
OPEN-CELL FOAM PADDING
BEMIS TONGUE OVERLAY
ARCH ACTIVATOR / MEDIAL LOCKDOWN STRAP
BEMIS TOE PROTECTION
DURABILITY PROTRUSIONS
TRANSLUCENT BEMIS WATER/MUD GUARD
SPACER MESH MAIN UPPER
PORON SOCKLINER
INJECTION-MOLDED TPU SOCKLINER STABILIZER
SENSOR ACCESS PORTAL
STROBEL BOARD

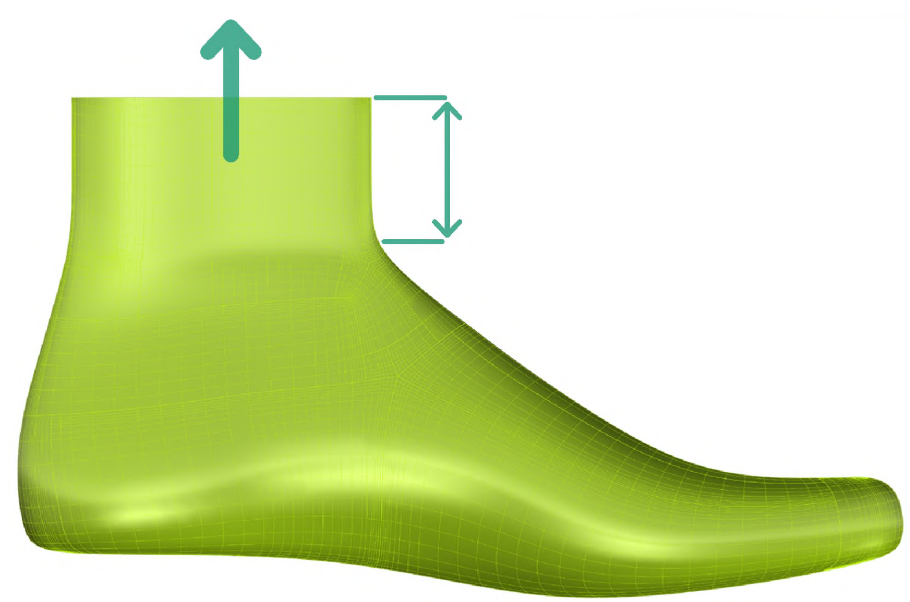
FINAL DESIGN INTENT

DEVELOPING A FEMALE-SPECIFIC LAST

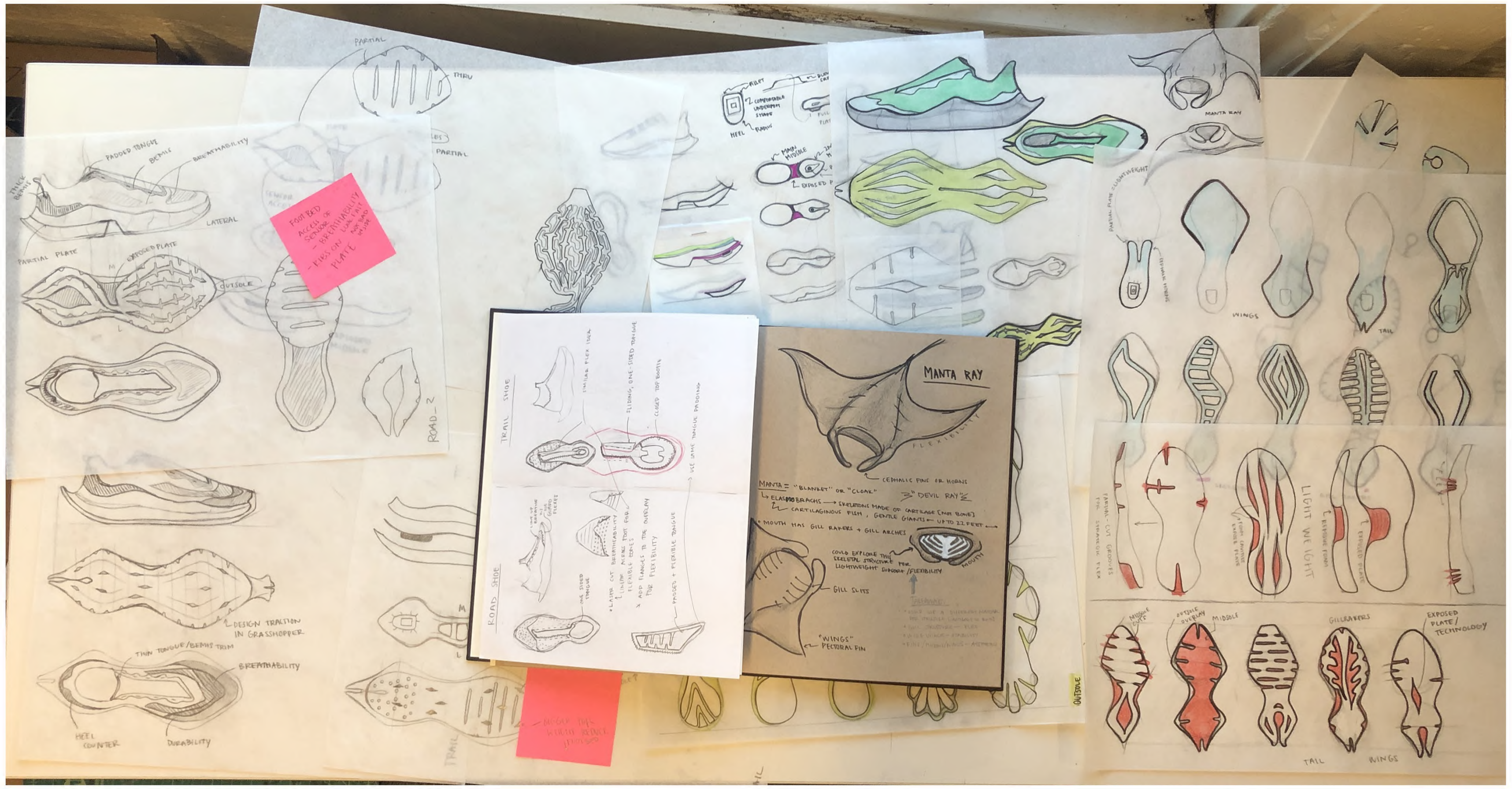


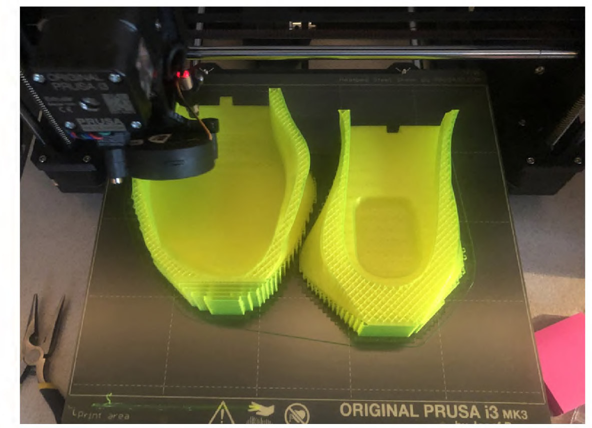






FEMALE-SPECIFIC UPDATES	
FEMALE FEET	NARROWER HEEL SHORTER @ HL TO 5TH MPJ NARROWER BALL OF FOOT WIDTH SHORTER ANKLE LENGTH SHORTER MEDIAL MALLEOUS HEIGHT HIGHER & MORE VARIABLE ARCH SMALLER INSTEP CIRCUMFERENCE
TYPICAL W8	65 MM HEEL BREADTH 90 MM FOREFOOT BREADTH 0 MM LAST HEIGHT
TAU TRAINER	60 MM HEEL BREADTH 94 MM FOREFOOT BREADTH 42 MM LAST HEIGHT

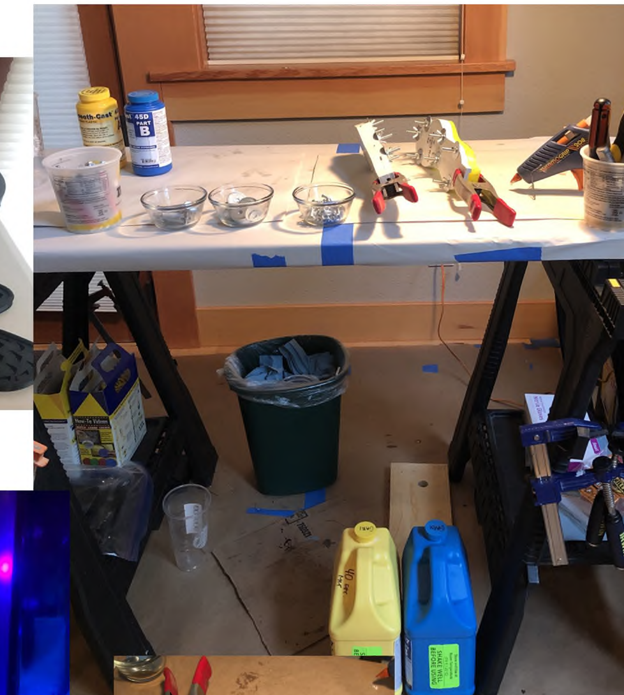

MANTA RAY

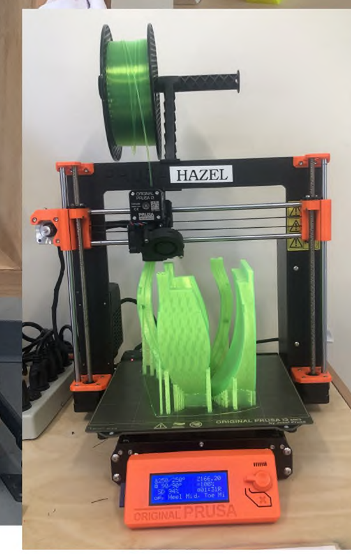

ORIGINAL PRUSA i3 MK3

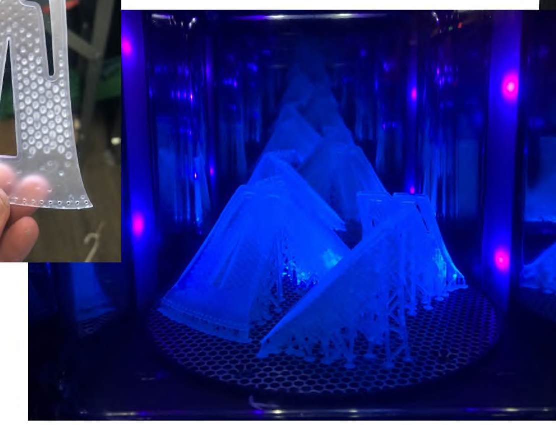

MEDIAL
MIDSOLE REMOVED TO SIDE FOR SENSOR ACCESS

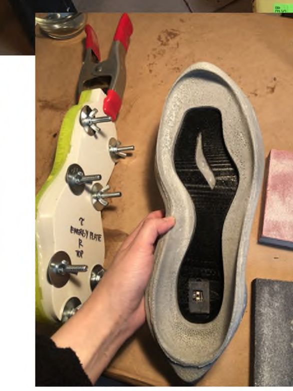
UPPER IDEATION

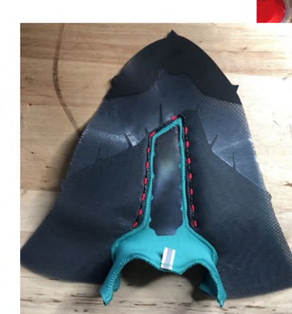
PROTOTYPING







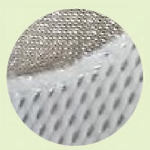




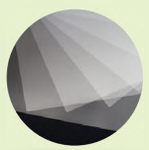
MATERIALS & MANUFACTURING

UPPER

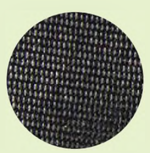
ROAD MATERIALS



WHITE SPACER MESH
100% POLYESTER, KNIT, 3MM THICK, 350 GSM

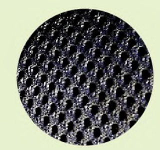


PROTECTIVE FILM
BEMIS TL644 - FORMFIT, ELASTOMERIC POLYURETHANE



BLACK KNIT LINING
100% POLYESTER + OPEN CELL PU FOAM FOR PADDING (4MM THICK)

TRAIL MATERIALS



BLACK SPACER MESH
100% POLYESTER, KNIT, 3MM THICK, 350 GSM, DWR FINISH

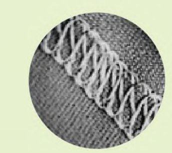
PROTECTIVE FILM
BEMIS RS3500 - RAINBOW, ELASTOMERIC POLYURETHANE

BLACK KNIT LINING
100% POLYESTER + OPEN CELL PU FOAM FOR PADDING (4MM THICK)

STITCHING

STROBEL

ZIG-ZAG



COVERSTITCH

SOLE UNIT

MIDSOLE

EVA FOAM
INJECTION MOLDED & ADHERED WITH BARGE CLEAR TF

FLEX-IT! FOAM 17
SMOOTH ON EXPANDING POLYURETHANE FOAM

ENERGY PLATE

THERMOPLASTIC POLYURETHANE
INJECTION MOLDED

ONYX SLOW LIQUID PLASTIC
SMOOTH CAST MERCURY-FREE URETHANE RESIN, ULTRA-BLACK

OUTSOLE

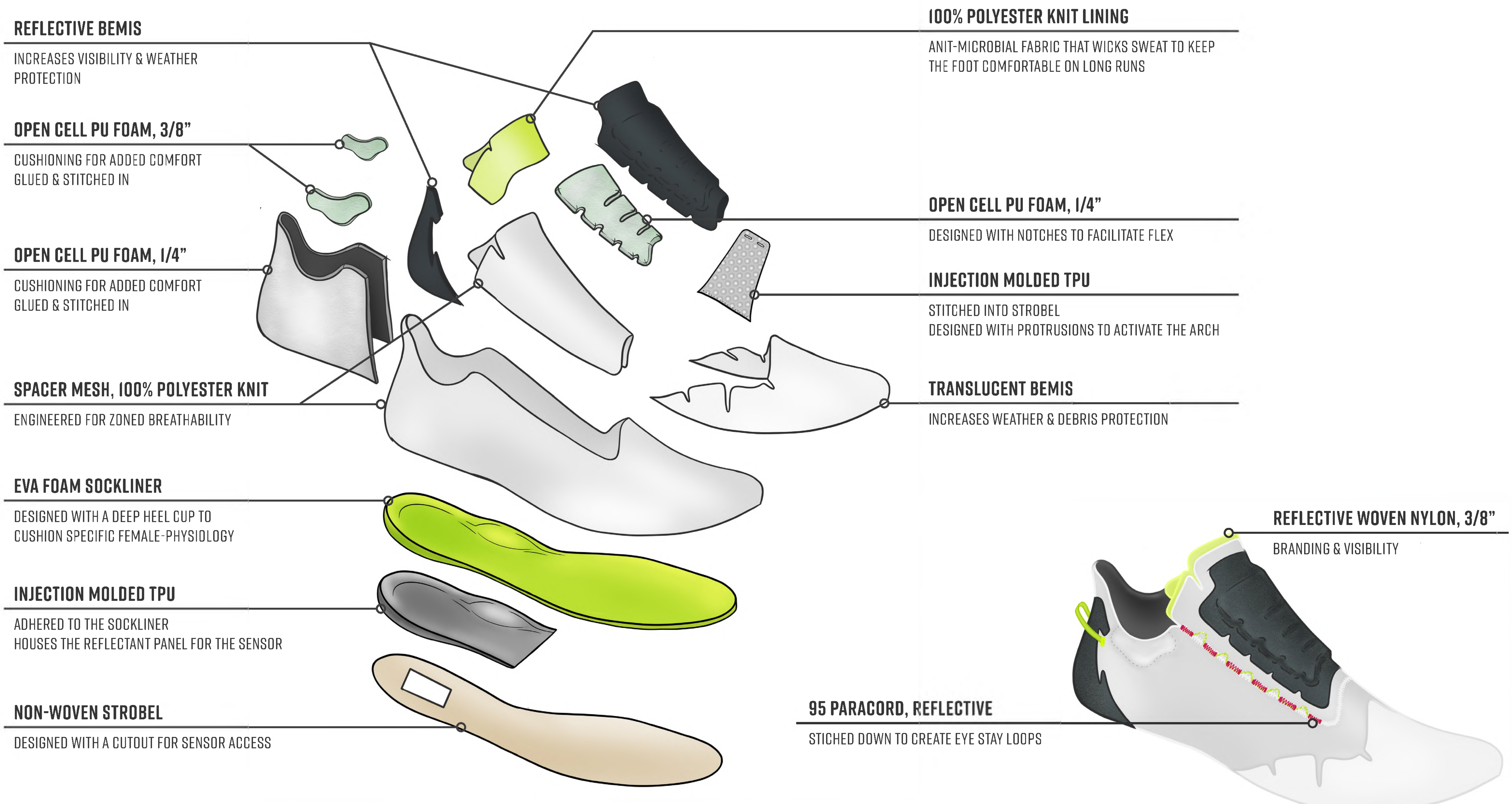
CARBON RUBBER
HYDRAULICALLY HEAT PRESSED & ADHERED WITH BARGE CLEAR TF

REOFLEX 60
SMOOTH ON URETHANE RUBBER, DYED WITH IGNITE FLUORESCENTS

FINAL DESIGN

CAD RENDERS, TECH PACK, COLORWAYS

TAU TRAINERS ROAD



ROAD FINAL DESIGN

PADDED TONGUE WITH CINCH LACES

NOTCHED FOAM FOR EXTRA COMFORT WITHOUT COMPROMISING FLEXIBILITY

CINCH LACES ALLOW QUICK LACING

POLYESTER, KNIT, SPACER MESH

DWR FINISH, EXTENDED WATER GUARD WITH FLEX-NOTCHES

SINGLE-SIDED TONGUE FOR DECREASED DEBRIS ENTRY

ACTIVO-ARCH, INJECTION MOLDED TPU

RAISED PROTRUSIONS

INCREASES LOCKDOWN & ARCH ACTIVATION

IMPULSE INTEGRATION SYSTEM

MULTI-LAYER CONSTRUCTION ENABLES THE QUANTIFICATION OF SHEAR DISPLACEMENT AT THE FOOT-SHOE INTERFACE

RLEAYS INFORMATION TO AN APP VIA BLUETOOTH

EVA FOAM MIDSOLE

HIGH SIDEWALLS FOR INCREASED STABILITY

MAXIMALIST STACK HEIGHT FOR INCREASED IMPACT ATTENUATION

TOTALIS TRACTION, CARBON BLOWN RUBBER OUTSOLE

ENGINEERED FLEX GROOVES & LEADING EDGES FOR MAXIMUM TRACTION ON WET SURFACES

EXTENDED TOE WRAP FOR INCREASED PROTECTION & DURABILITY

POLYESTER, KNIT, SOCKLINER

EVA FOAM FEMALE-SPECIFIC INSOLE

DEEP HEEL CUP TO FACILITATE IMPACT ATTENUATION

INSOLE SHELL

TPU INJECTION MOLDED, INCREASES STABILITY

HOUSES THE REFLECTANT PANEL THAT THE SENSOR READS

EVA FOAM MODERATOR SCOPE

ALLOWS SHEAR STRESS TO BE QUANTIFIABLY MEASURED

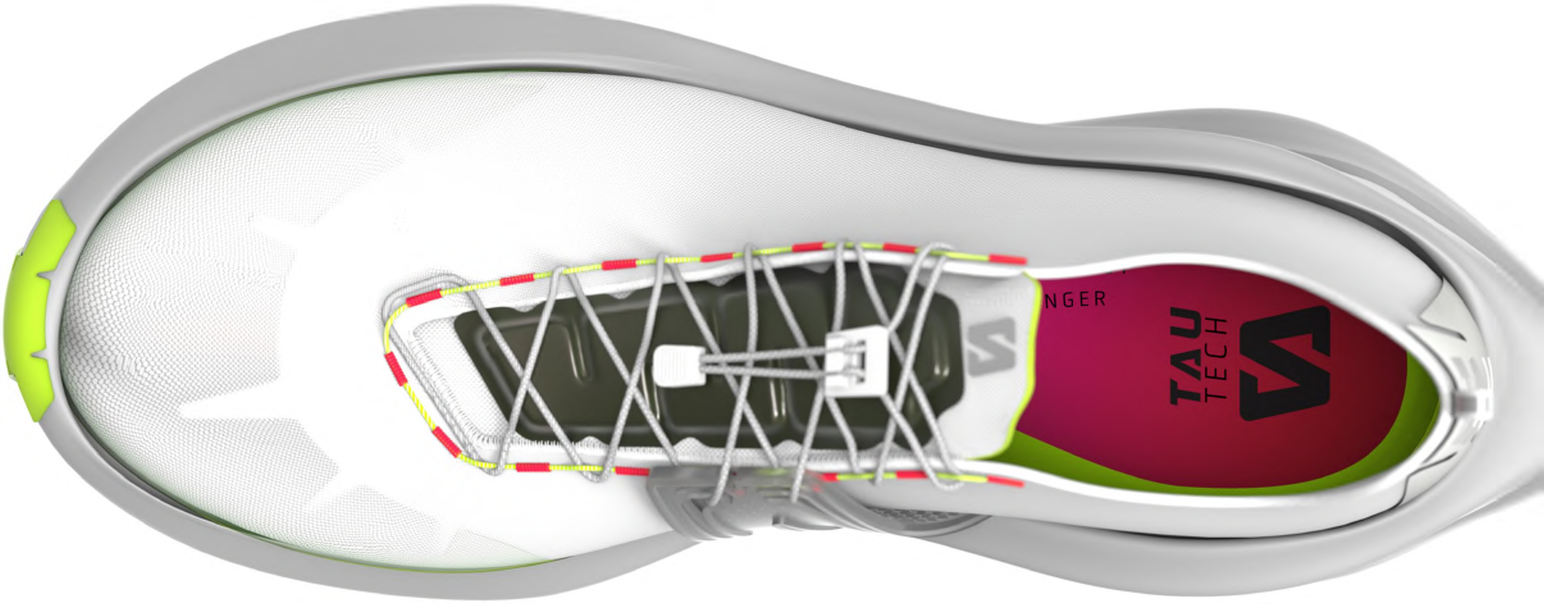
TAU-TECH & ACCESS PANEL

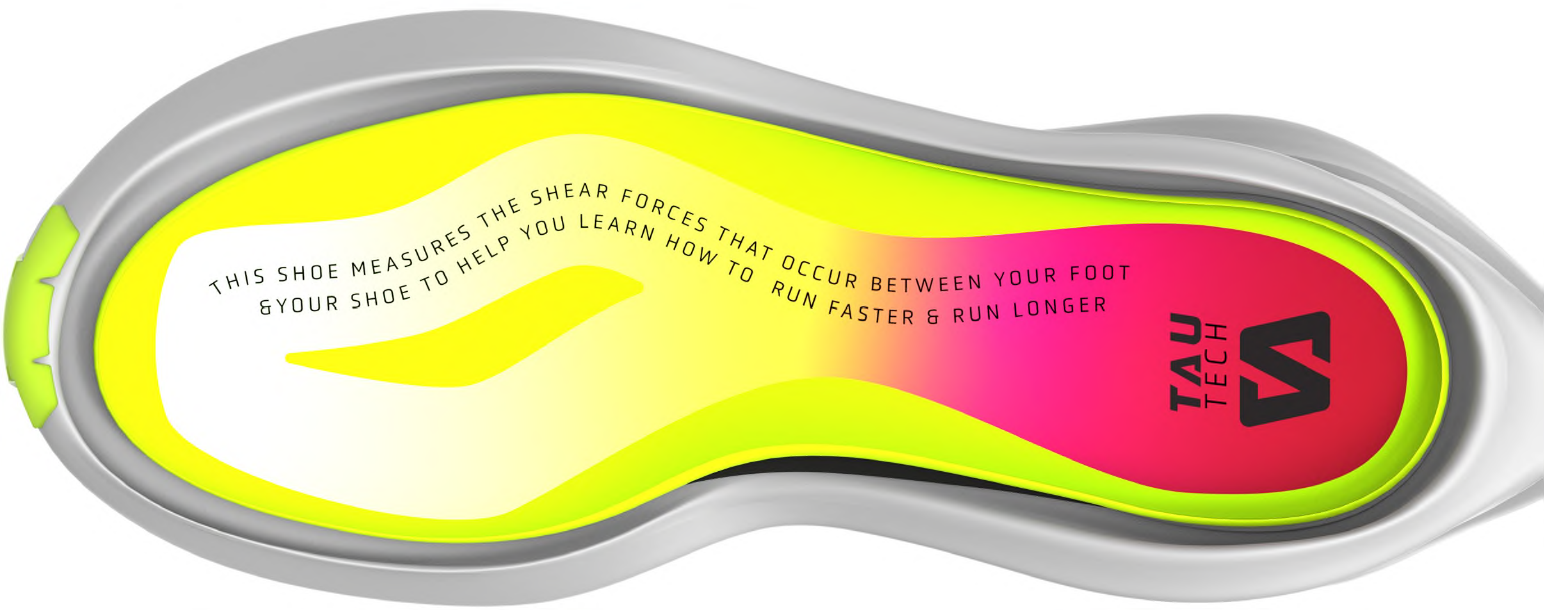
EVA FOAM INNER MIDSOLE

TPU INJECTION MOLDED PLATE

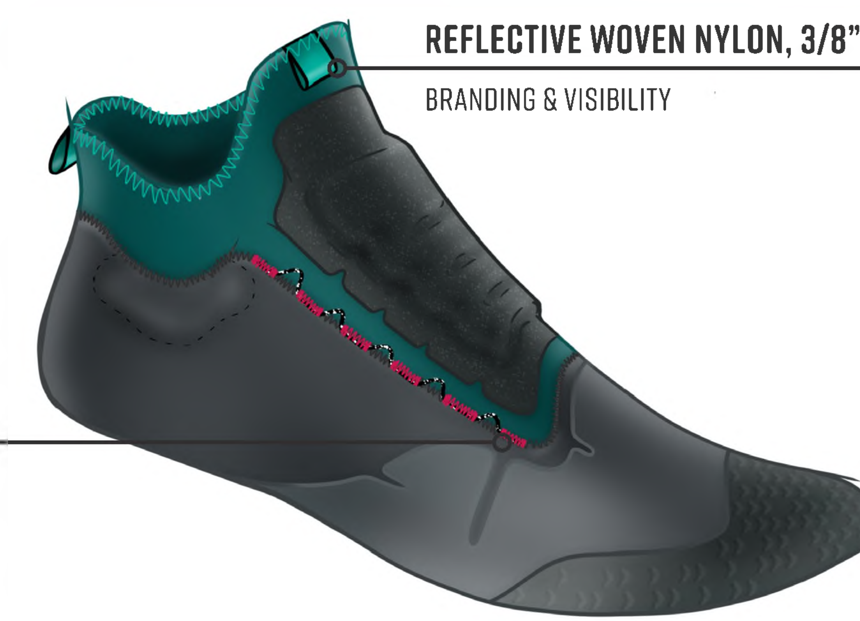
SECURELY HOUSES THE SENSOR & INCREASES ENERGY RETURN

EVA FOAM OUTER MIDSOLE


TAU
TECH


THIS SHOE MEASURES THE SHEAR FORCES THAT OCCUR BETWEEN YOUR FOOT
&YOUR SHOE TO HELP YOU LEARN HOW TO RUN FASTER & RUN LONGER
TAU
TECH

TAU TRAINERS TRAIL



TRAIL FINAL DESIGN

PADDED TONGUE WITH CINCH LACES

NOTCHED FOAM FOR EXTRA COMFORT WITHOUT COMPROMISING FLEXIBILITY

CINCH LACES ALLOW QUICK LACING

POLYESTER, KNIT, SPACER MESH

DWR FINISH, EXTENDED WATER GUARD WITH FLEX-NOTCHES

EXTRA TOE-PROTECTION FOR INCREASED DURABILITY

MID-HEIGHT BOOTIE FOR DECREASED DEBRIS ENTRY

ACTIVO-ARCH, INJECTION MOLDED TPU

RAISED PROTRUSIONS

INCREASES LOCKDOWN & ARCH ACTIVATION

IMPULSE INTEGRATION SYSTEM

MULTI-LAYER CONSTRUCTION ENABLES THE QUANTIFICATION OF SHEAR DISPLACEMENT AT THE FOOT-SHOE INTERFACE

RLEAYS INFORMATION TO AN APP VIA BLUETOOTH

EVA FOAM MIDSOLE

HIGH SIDEWALLS FOR INCREASED STABILITY

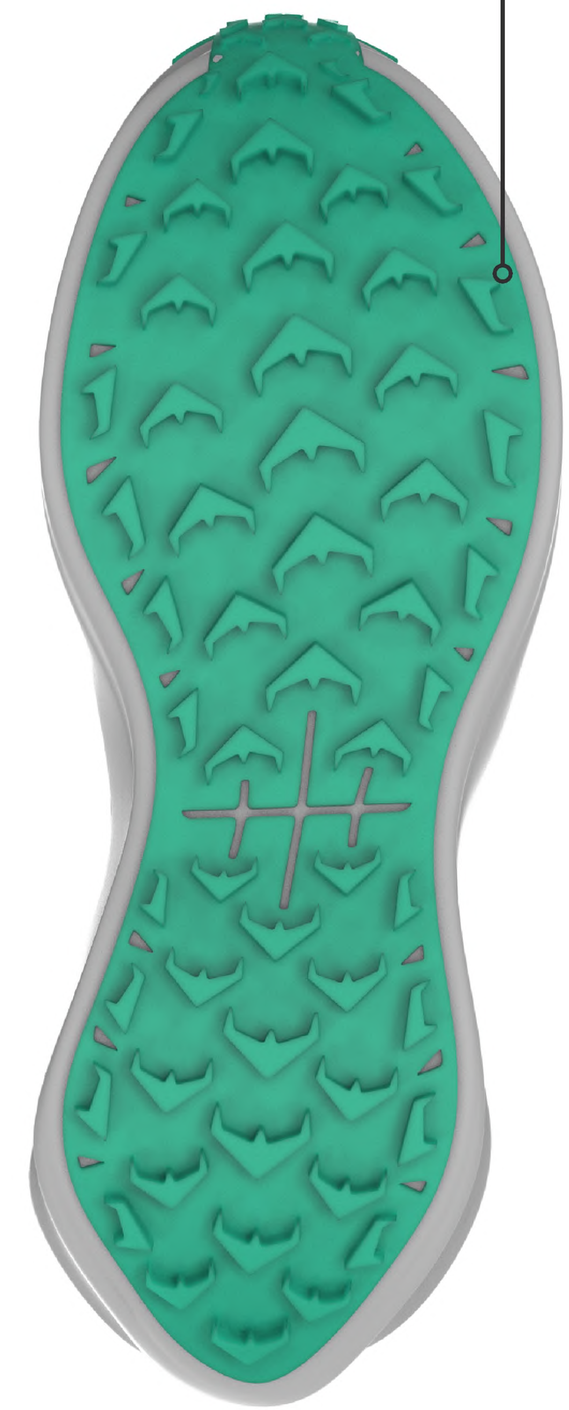
MAXIMALIST STACK HEIGHT FOR INCREASED IMPACT ATTENUATION

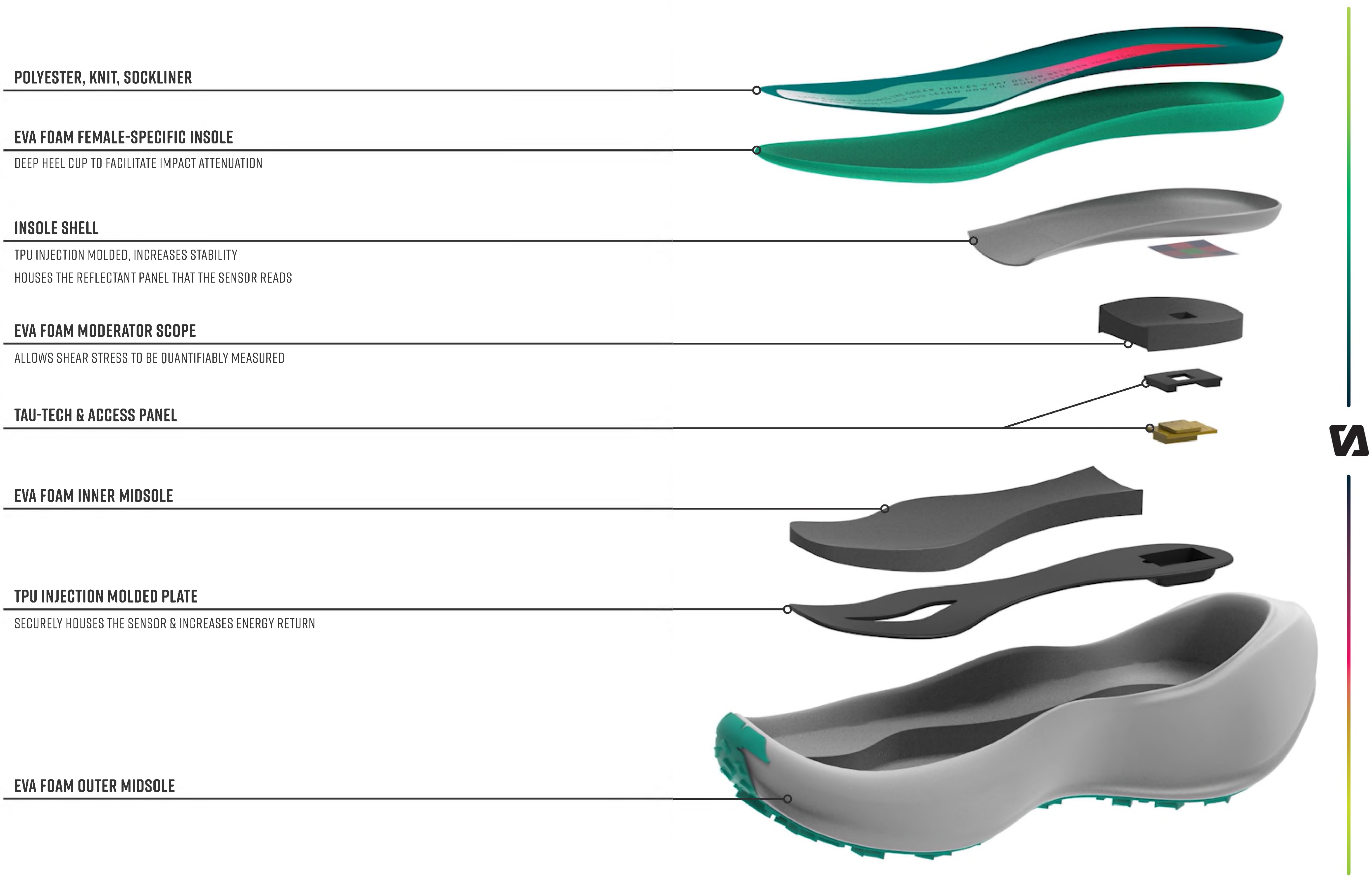
NARROW FOOTPRINT FOR ENHANCED CONTROL

TOTALIS TRACTION, CARBON BLOWN RUBBER OUTSOLE

MULTI-DIRECTIONAL, 4MM LUGS ENGINEERED TO GRIP THE TRAIL, WET OR DRY

EXTENDED TOE WRAP FOR INCREASED PROTECTION & DURABILITY




POLYESTER, KNIT, SOCKLINER
EVA FOAM FEMALE-SPECIFIC INSOLE
DEEP HEEL CUP TO FACILITATE IMPACT ATTENUATION
INSOLE SHELL
TPU INJECTION MOLDED, INCREASES STABILITY
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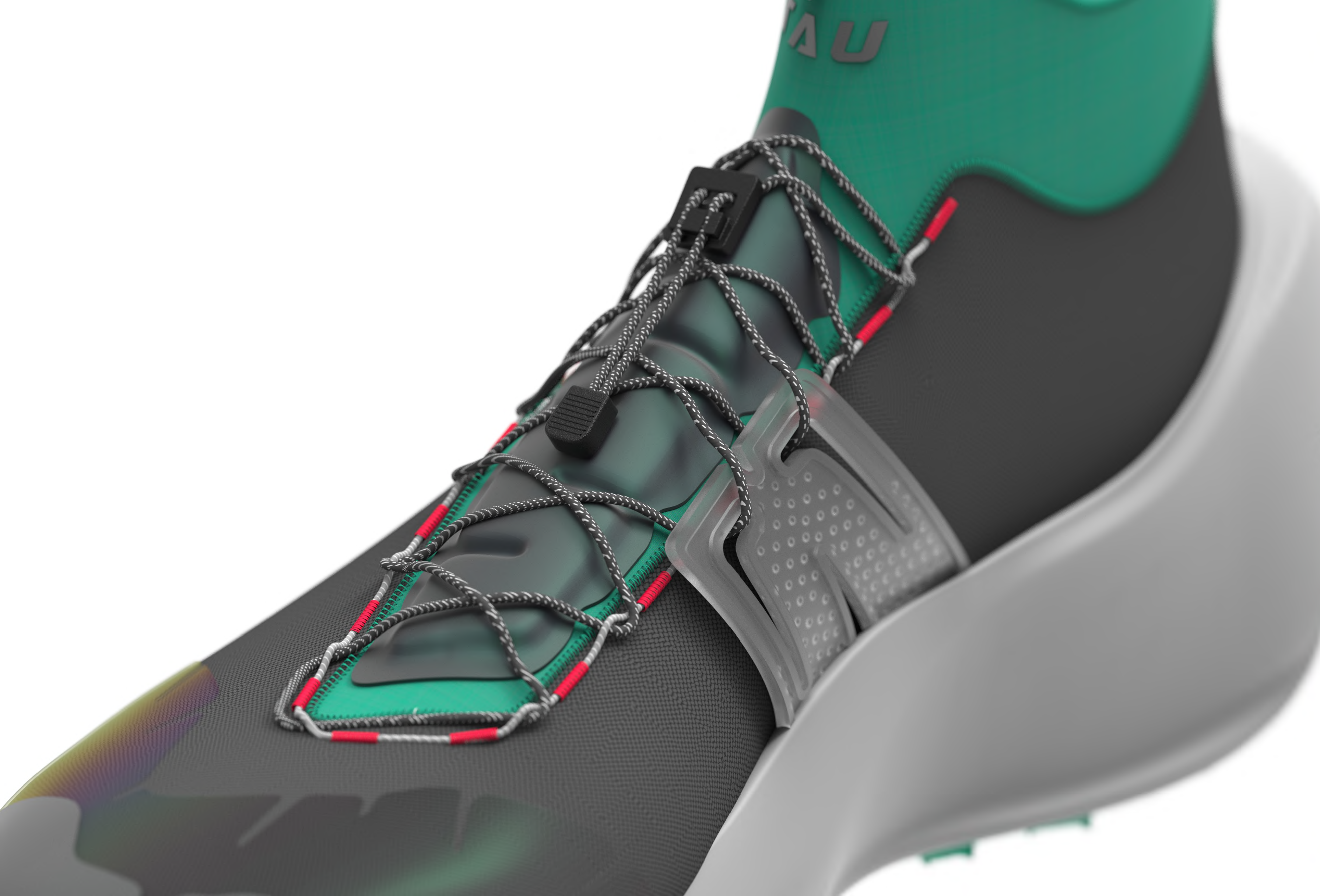
TAU-TECH & ACCESS PANEL
EVA FOAM INNER MIDSOLE
TPU INJECTION MOLDED PLATE
SECURELY HOUSES THE SENSOR & INCREASES ENERGY RETURN
EVA FOAM OUTER MIDSOLE




THIS SHOE MEASURES THE SHEAR FORCES THAT OCCUR BETWEEN YOUR FOOT
&YOUR SHOE TO HELP YOU LEARN HOW TO RUN FASTER & RUN LONGER
TAU
TECH


TAU
TECH

ROAD COLORWAYS

SUNLIT LIME

XX-XXXX TCX	WHITE
12-0703 TCX	SEEDPEARL
14-0340 TCX	ACID LIME
12-0741 TCX	SUNNY LIME
18-1856 TCX	VIRTUAL PINK

HOT RIVER

XX-XXXX TCX	HOT ASH
12-0703 TCX	SEEDPEARL
19-5217 TCX	ACID LIME
16-5425 TCX	POOL GREEN
18-1856 TCX	VIRTUAL PINK

CLASSIC TEAL

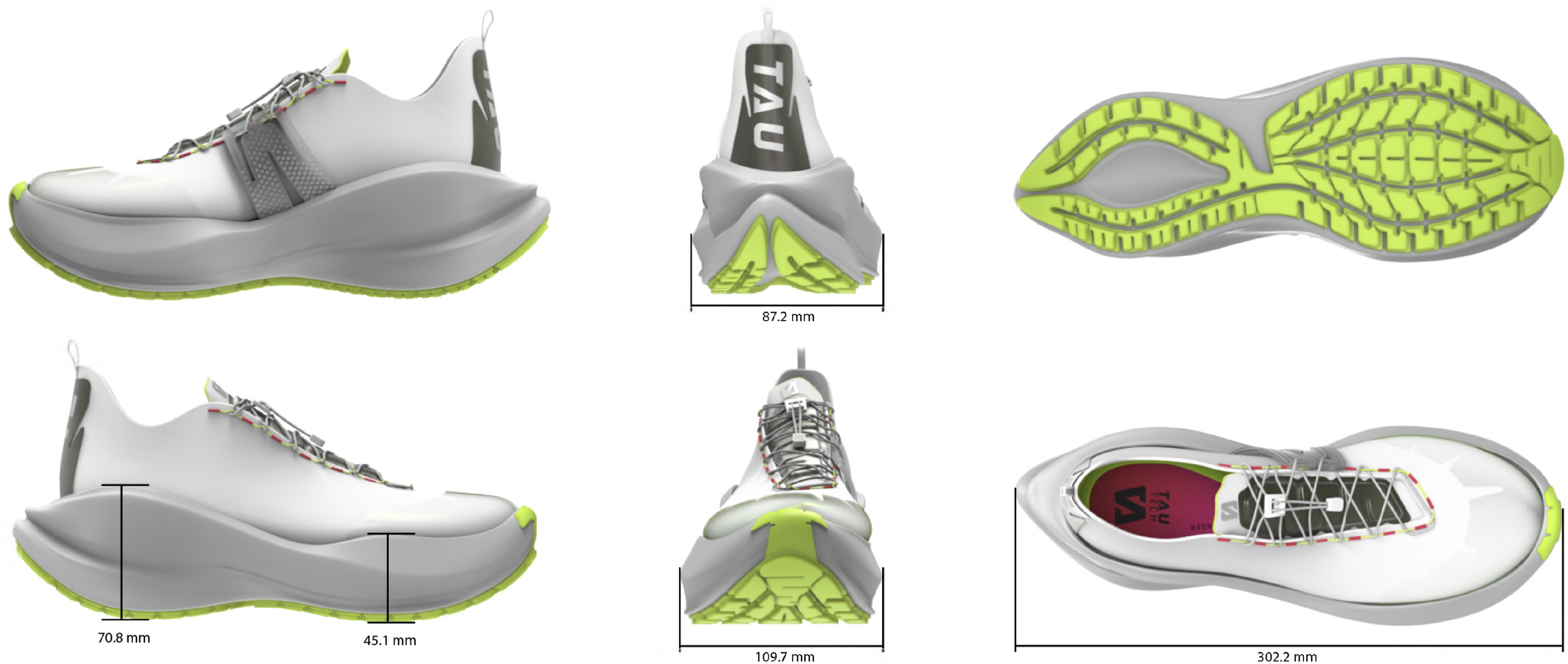
XX-XXXX TCX	HOT ASH
XX-XXXX TCX	MOLTEN GREY
15-4305 TCX	QUARRY
12-0703 TCX	SEEDPEARL
16-5425 TCX	POOL GREEN

TRAIL COLORWAYS

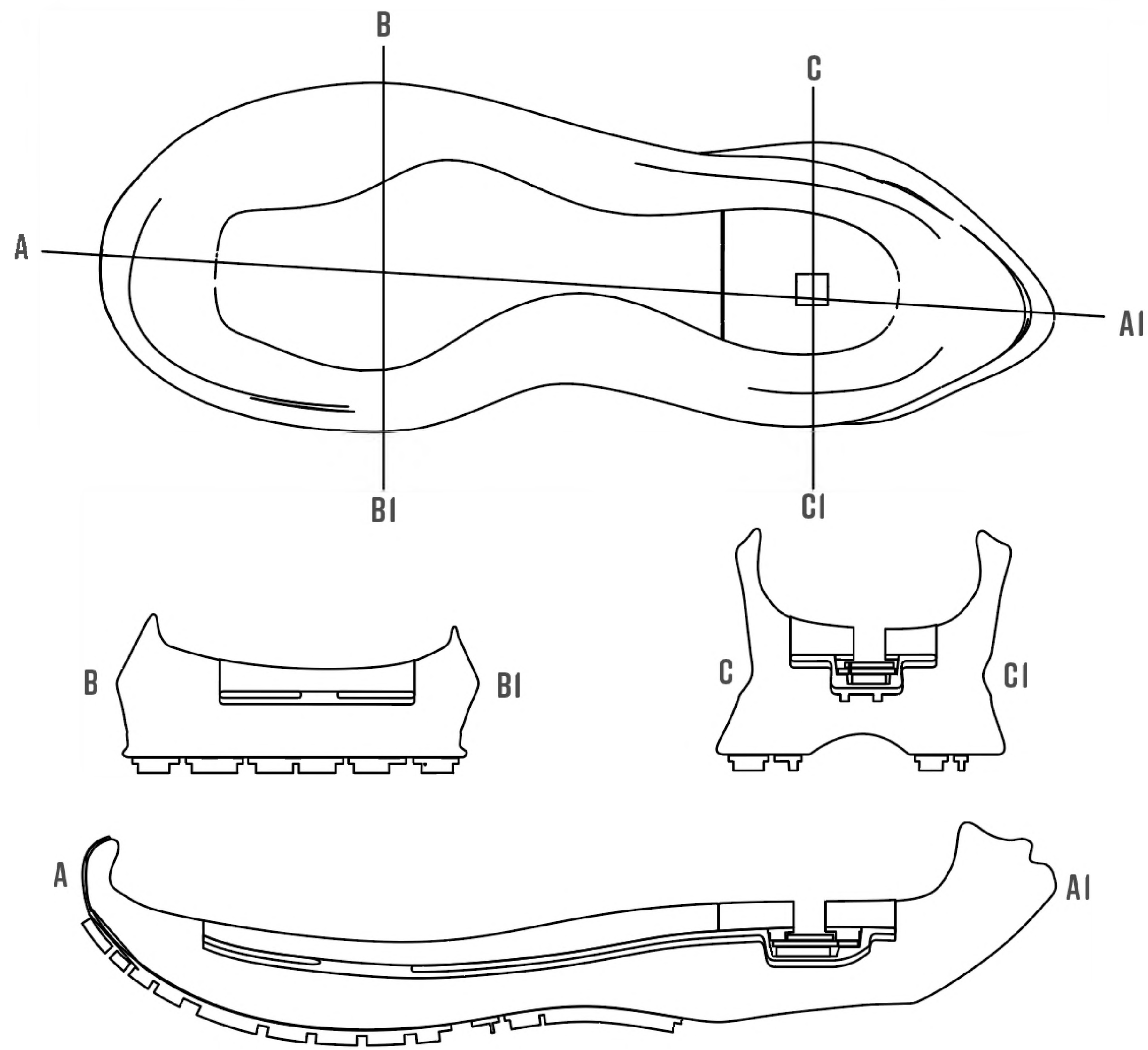
RIVER BED	
19-4405 TCX	FOREST RIVER
15-4305 TCX	QUARRY
19-5217 TCX	STORM
16-5425 TCX	POOL GREEN
18-1856 TCX	VIRTUAL PINK

GOODNIGHT LIME	
XX-XXXX TCX	HOT ASH
XX-XXXX TCX	MOLTEN GREY
14-0340 TCX	ACID LIME
12-0741 TCX	SUNNY LIME
16-5425 TCX	POOL GREEN

MIDNIGHT TANGERINE	
XX-XXXX TCX	SLEEPY PLUM
12-0703 TCX	SEEDPEARL
XX-XXXX TCX	HOT ASH
XX-XXXX TCX	TANGERINE
XX-XXXX TCX	DUSK DUST



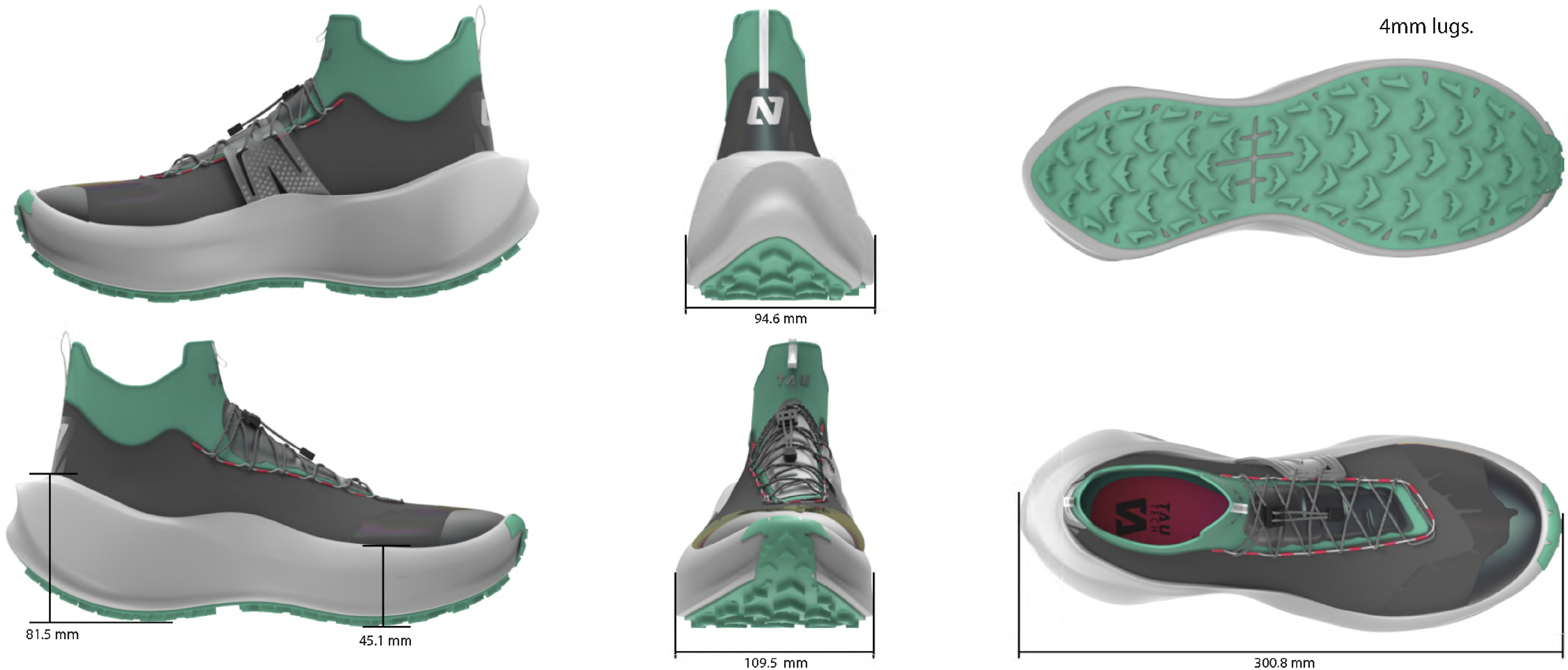
TAU TRAINERS - ROAD	REFERENCE CAD FILES FOR DETAILED DIMENSIONS.	Designer: Gabi Lorenzo
Colorway: Sunlit Lime	REFERENCE PREVIOUS PAGES FOR COLOR TCX.	Last Updated: 6/8/2022
Size Reference: Women's 8	REFERENCE PREVIOUS PAGES FOR MATERIALS.	Page 1/4



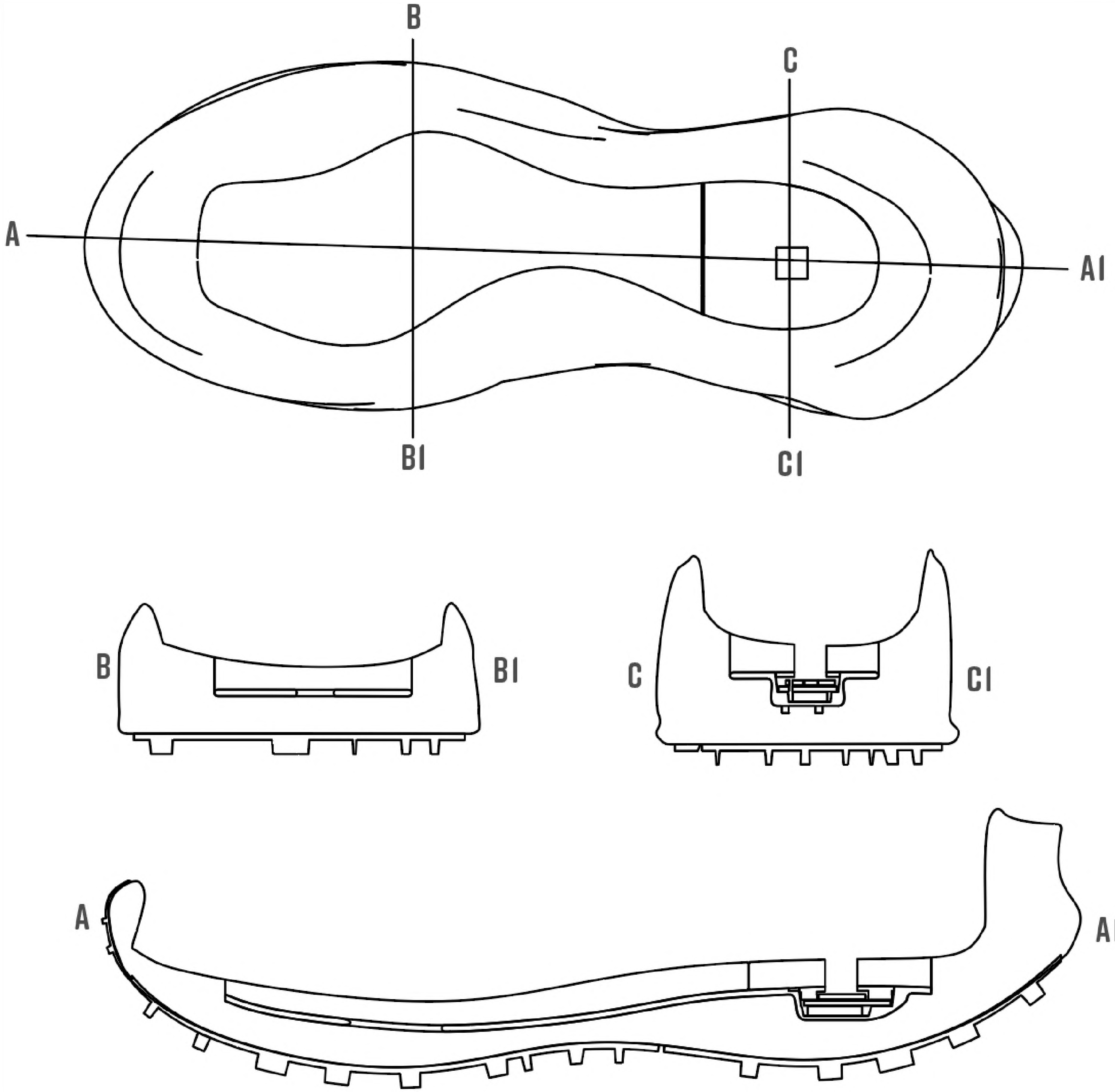
35 mm stack height.

Contact Sensor Team for sensor design specifications.

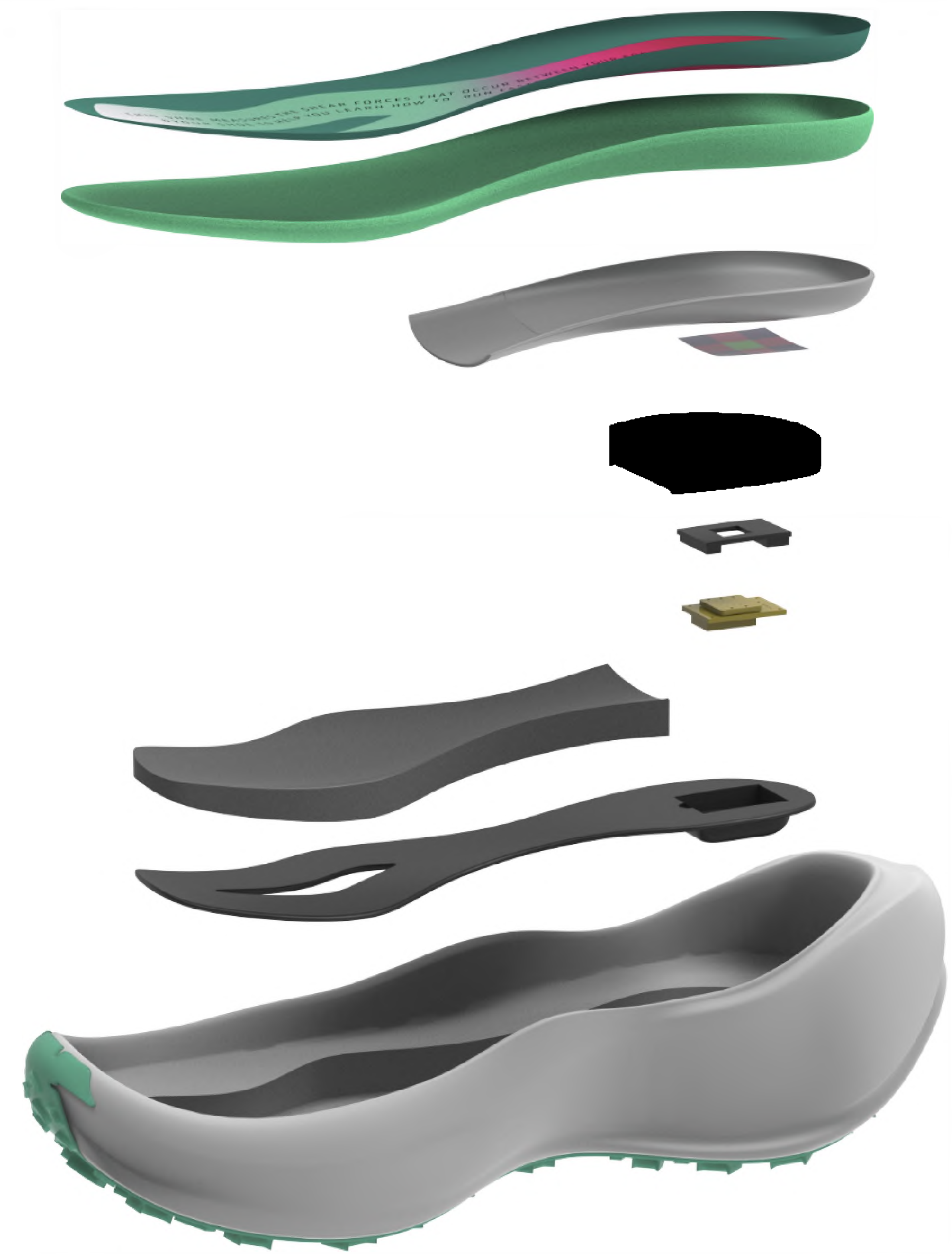
TAU TRAINERS - ROAD	REFERENCE CAD FILES FOR DETAILED DIMENSIONS.	Designer: Gabi Lorenzo
Colorway: Sunlit Lime	REFERENCE PREVIOUS PAGES FOR COLOR TCX.	Last Updated: 6/8/2022
Size Reference: Women's 8	REFERENCE PREVIOUS PAGES FOR MATERIALS.	Page 2/4



TAU TRAINERS - TRAIL	REFERENCE CAD FILES FOR DETAILED DIMENSIONS.	Designer: Gabi Lorenzo
Colorway: River Bed	REFERENCE PREVIOUS PAGES FOR COLOR TCX.	Last Updated: 6/8/2022
Size Reference: Women's 8	REFERENCE PREVIOUS PAGES FOR MATERIALS.	Page 3/4



29 mm stack height.



Contact Sensor Team for sensor design specifications.

TAU TRAINERS - TRAIL

Colorway: River Bed

Size Reference: Women's 8

REFERENCE CAD FILES FOR DETAILED DIMENSIONS.

REFERENCE PREVIOUS PAGES FOR COLOR TCX.

REFERENCE PREVIOUS PAGES FOR MATERIALS.

Designer: Gabi Lorenzo

Last Updated: 6/8/2022

FINAL PROTOTYPES

ROAD & TRAIL


TAU

FINAL ROAD PROTOTYPE


TAU

FINAL TRAIL PROTOTYPE

VALIDATION

FINAL TESTING & EXPERT FEEDBACK

EXPERT VALIDATION

WHAT WAS DISCUSSED?

1 MIKE MCGEEHAN
- Validation of sensor integration
- He will help analyze sensor data

2 EMILY KAROLIDIS
- Female fit validation
- Last shape, arch activation, etc.

3 EVAN DAY
- Footwear design for optimal performance & underfoot comfort

TEAM OF EXPERTS

BIOMECH. & ENGR.
BSSC & KNIGHT CAMPUS

MIKE MCGEEHAN

FEMALE BIOMECHANICS
BOWERMAN SPORTS SCIENCE CENTER

EMILY KAROLIDIS

DESIGN & DEVELOPMENT
BROOKS RUNNING

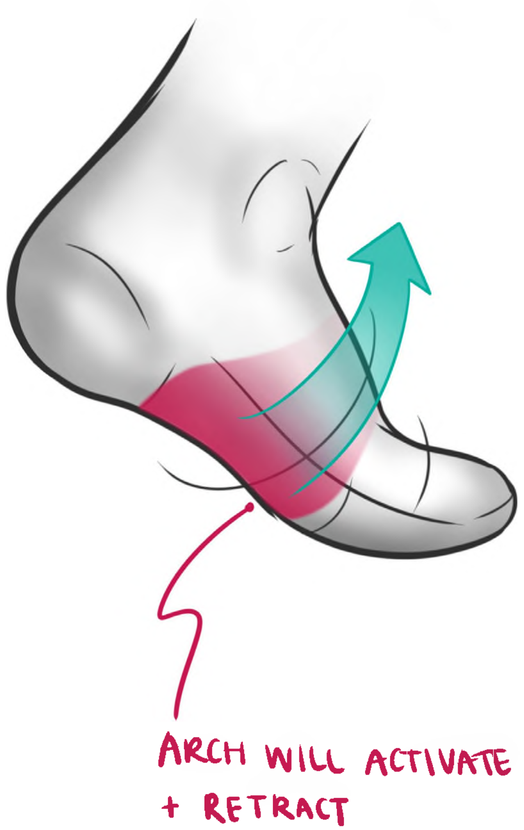
EVAN DAY

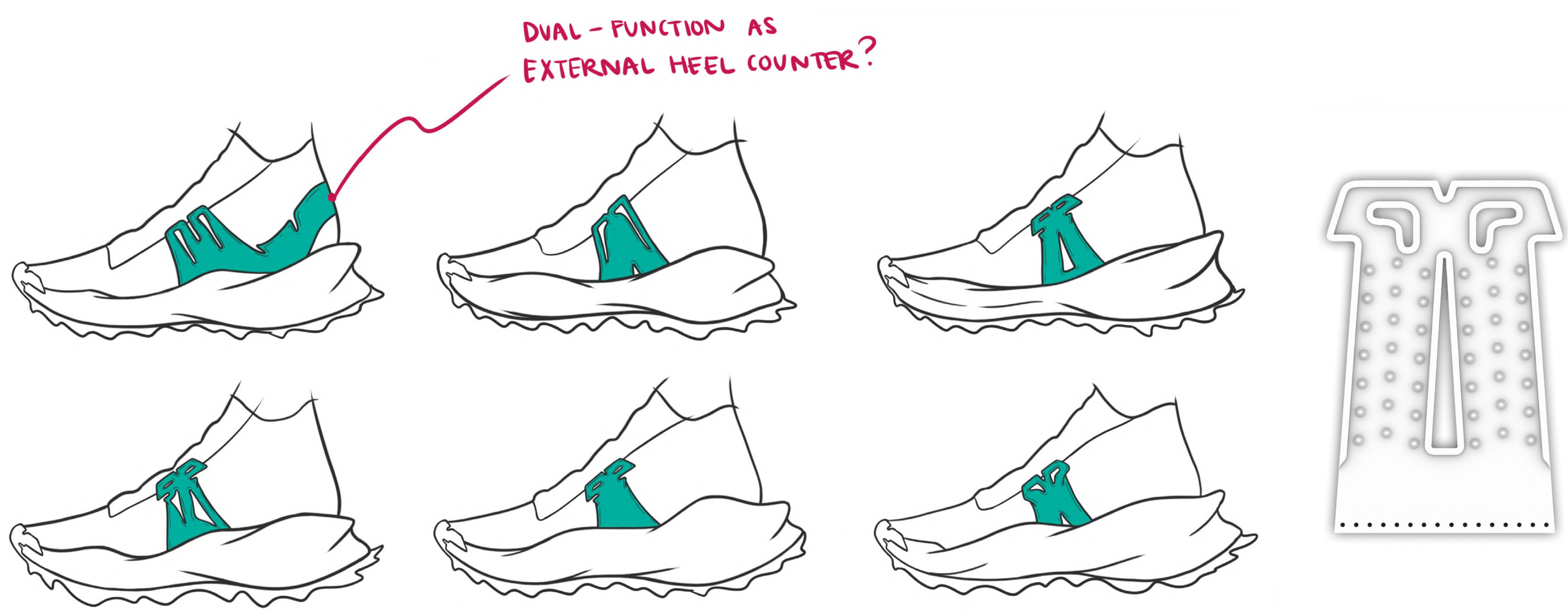
- Mike & I met/did some testing last week. He is happy with the sensor integration & believes it is very accurate/has been proven to be successful.
- Emily & I met. She helped me with some planning for the wear tests/validation techniques. She believes the process I went through to design the last was successful & is interested in how the arch activation strap can increase arch support (she did not know much about arch activation but her comments are on the next slide).
- I met with my design mentor, Evan Day, & got a ton of helpful feedback. I implemented this feedback into my final renders (mainly feedback on midsole, with a few outsole tweaks; he thought the uppers were looking good, & said the arch activator strap would be more powerful if told as a method of increasing athlete perception of the shoe & for the trail to focus on how it can increase lockdown especially on declines/downhill trails) & future prototypes. You can see his comments consildated in sketch/notation form on the second to next slide.

EXPERT VALIDATION

EMILY KAROLIDIS

"You will get some proprioceptive feedback and the arch will be aware [of the arch activation strap]. I'm not sure if there will be a helpful mechanical movement that will occur. However, proprioception does have observable benefits & can trigger the arch. The strap will definitely help athletes feel more secure, locked in, and can increase confidence. It is just important to make sure that it does not aggrevate the foot; you could attempt to validated the strap by looking at the pressure loading at the arch."





CONSILDATED FEEDBACK FROM EVAN DAY (BROOKS RUNNING), DESIGN MENTOR

FEMALE FIT VALIDATION

ATHLETE FEEDBACK

1 DISCOMFORTS

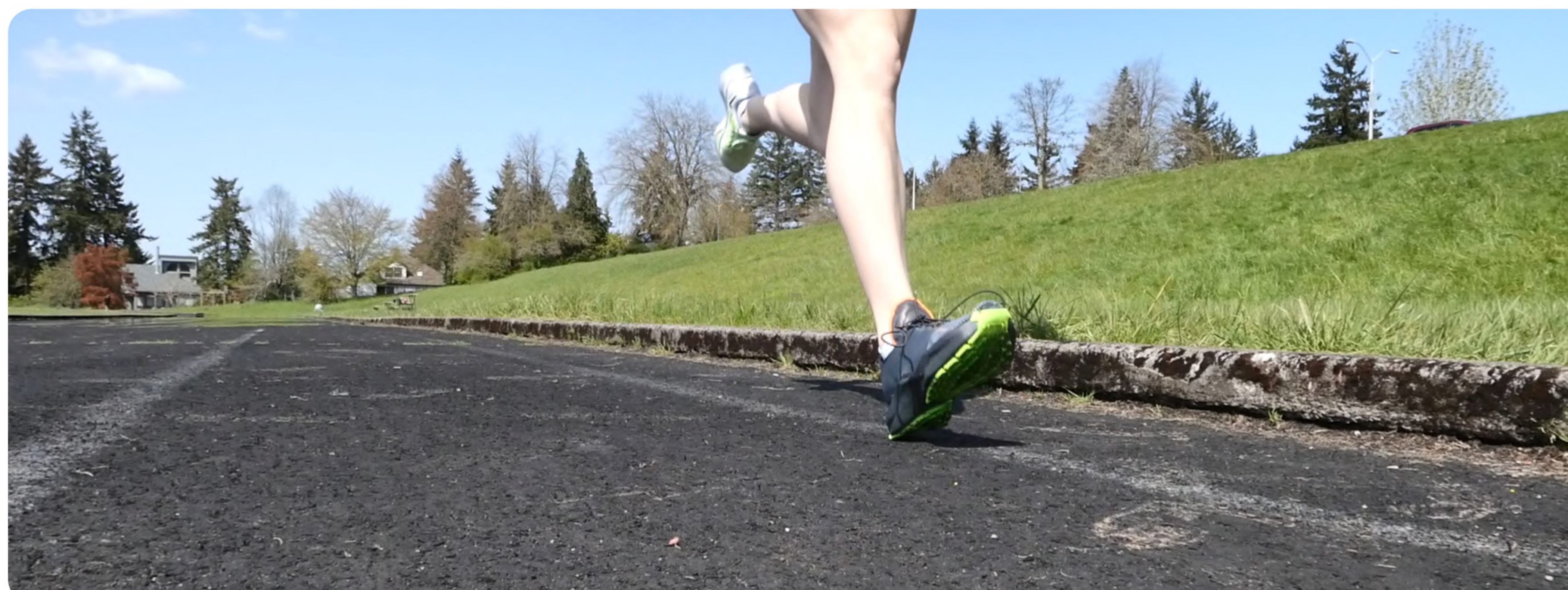
- Athletes did not believe there was enough cushioning in the midsole in both the sensor-equipped & regular midsole versions
- Stability should be improved within the heel
- Transition/ride of the sensor-equipped version can be better

2 POSITIVES

- Athletes loved the aesthetics
- Overall fit of the upper/footbed
- Traction performed well on various surfaces

3 NEXT STEPS

- Not much can be done about cushioning as discomfort is probably due to lack of industry standard materials
- Add an internal heel counter to both uppers
- Transition/ride of shoe will be improved since sensor size will be 50% of original



WEAR TEST PERCEPTIONS

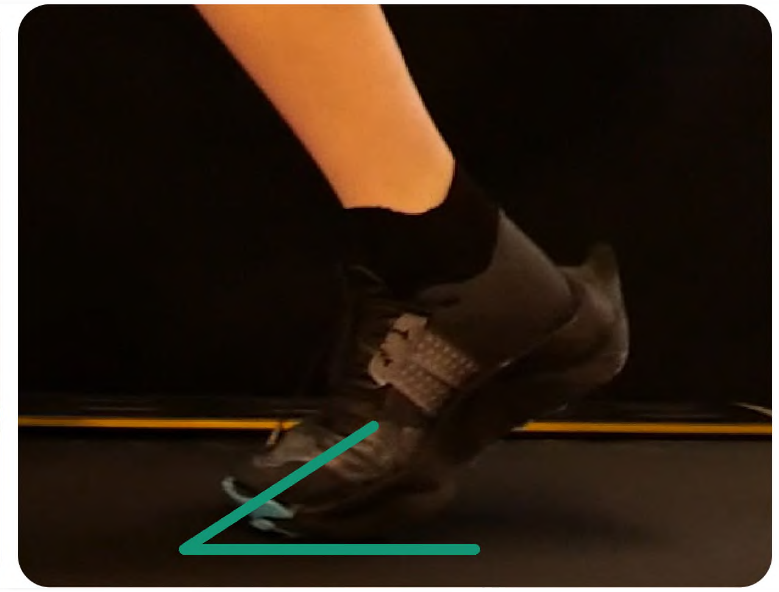
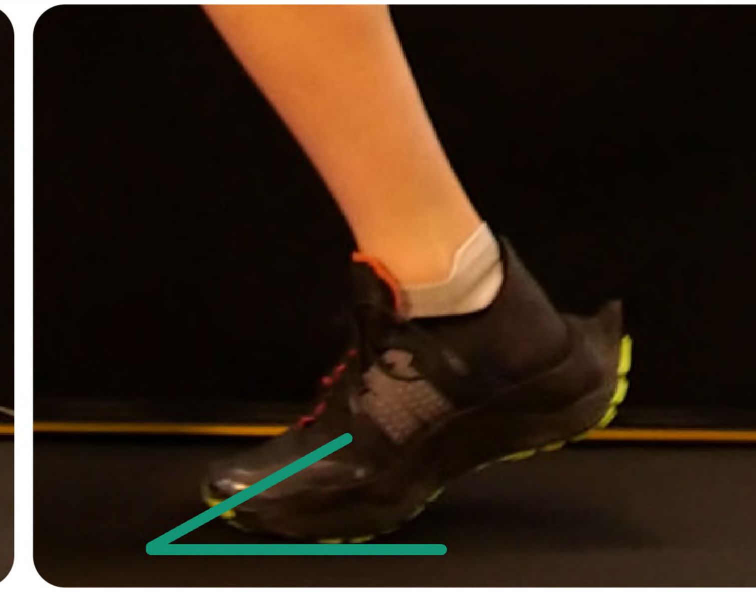
	COMFORT	CUSHIONING	VENTILIATION	ENERGY RET.	AESTHETICS	OVERALL*
	7.7 /10	6.2 /10	5.8 /10	6.4 /10	7.4 /10	7.0 /10
	7.3 /10	7.8 /10	5.4 /10	7.5 /10	6.6 /10	6.9 /10
	7.0 /10	6.5 /10	4.0 /10	5.0 /10	9.7 /10	6.7 /10
	6.0 /10	5.0 /10	5.5 /10	5.0 /10	9.7 /10	6.9 /10

OF PARTICIPANTS 03

*OVERALL RANKING IS DETERMINED BY AVERAGING THE WEAR TESTERS' RANKS OF PERCEIVED COMFORT AT 5 MINUTES, TRACTION, CUSHIONING, STABILITY, BREATHABILITY, ENERGY RETURN, FIT, & AESTHETICS.

FLEXIBILITY VALIDATION



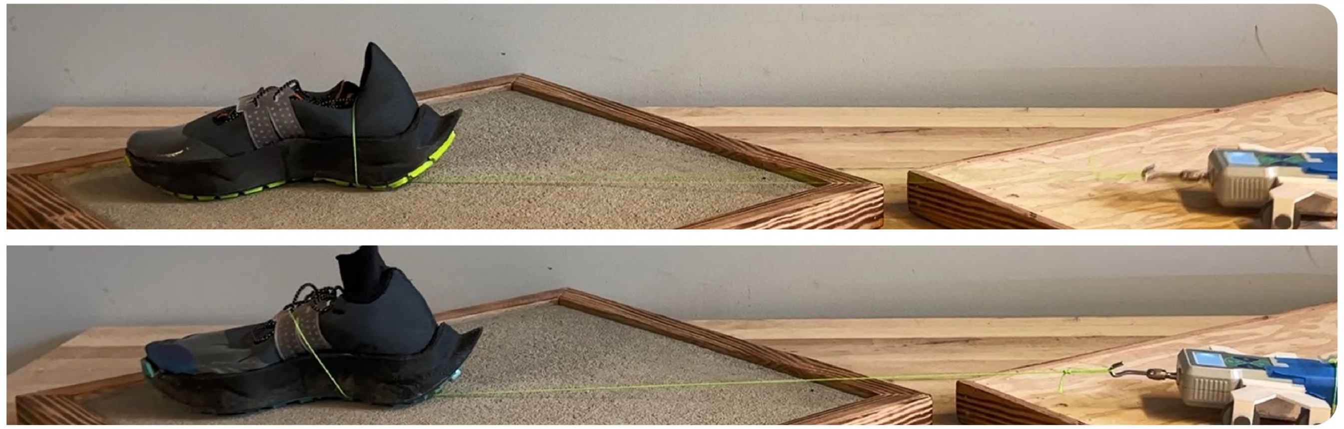
DATA ANALYSIS

- It's very difficult to accurately quantify this information, but I believe my prototypes pass because they clearly flex successfully.
- The flex values are also in a similar range to the baseline competitor products.
- Additionally, there were no complaints about flexibility from the various wear testers who wore the products on the treadmill, track, & trail.


PEGASUS TRAIL 3	PEGASUS 38	TAU TRAINERS TRAIL	TAU TRAINERS ROAD
29 DEGREES	27 DEGREES	36 DEGREES	32 DEGREES

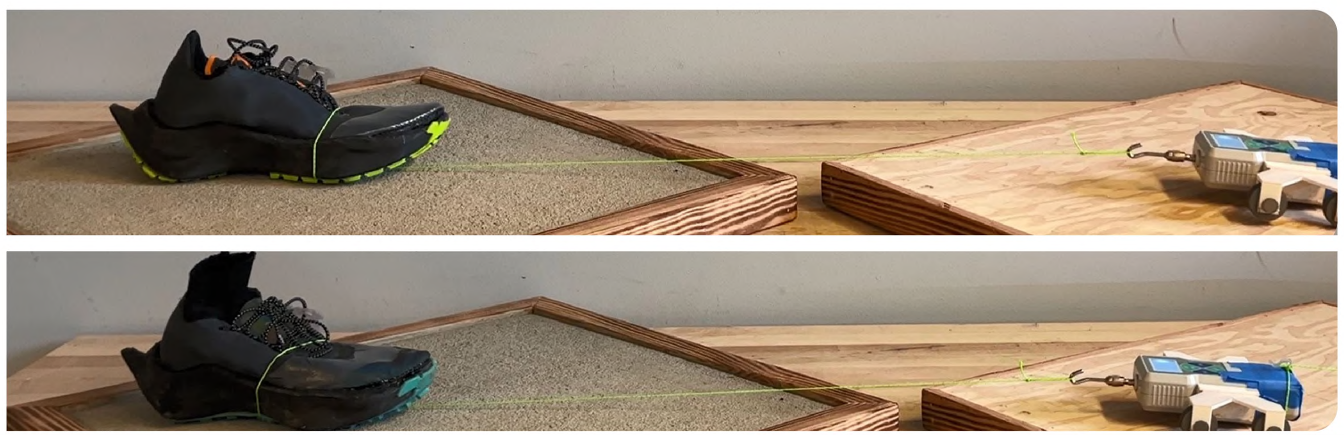
TOTALIS TRACTION TESTING

PROPULSION

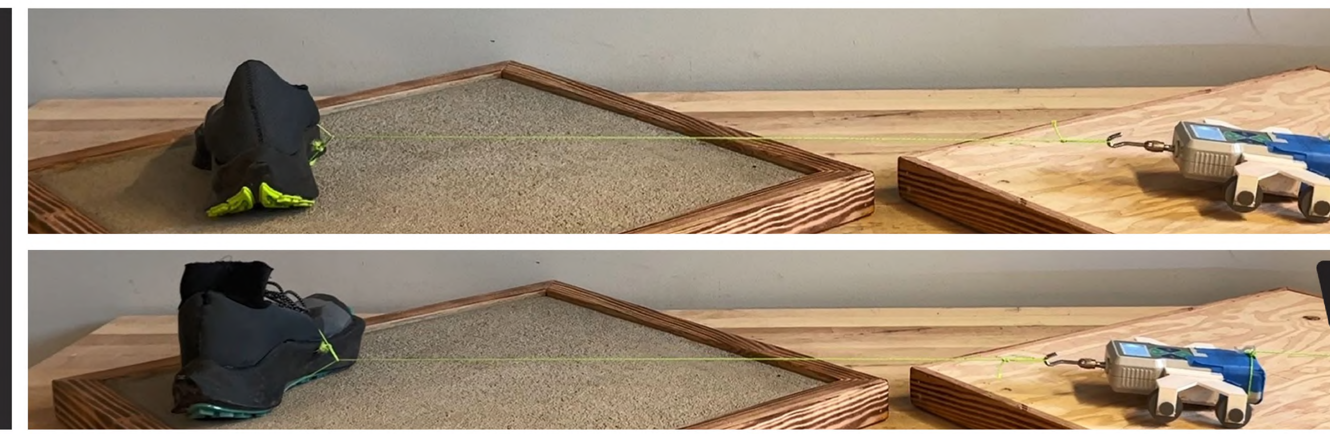


LATERAL

BRAKING



MEDIAL



AVG. TESTING RESULTS

TOTALIS ROAD TRACTION

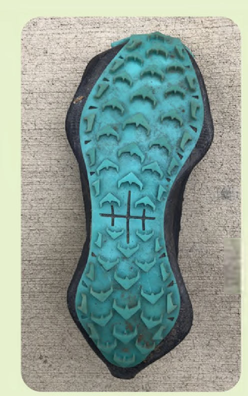
13.7 NEWTONS

10% GREATER THAN COMPETITORS [12.4 N]

14.8 NEWTONS

4% GREATER THAN COMPETITORS [14.2 N]

TOTALIS TRAIL TRACTION



12.7 NEWTONS

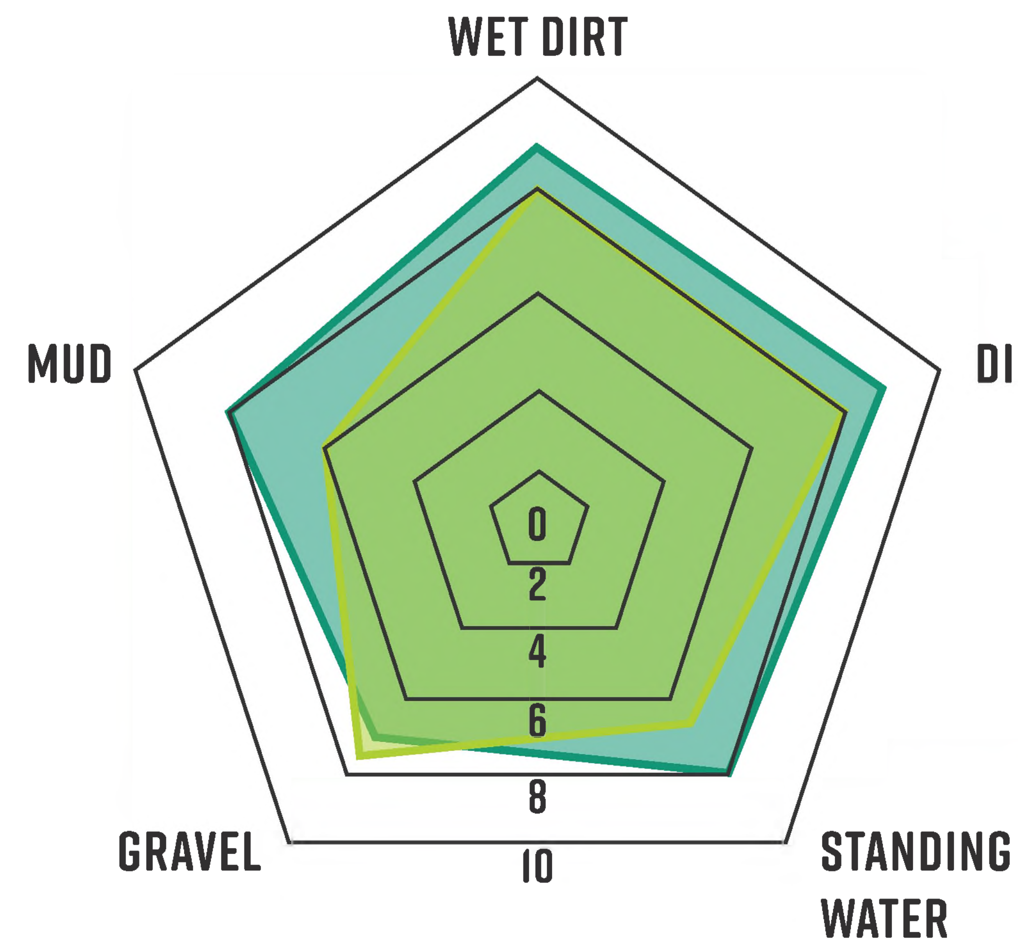
2% GREATER THAN COMPETITORS [12.4 N]

15.0 NEWTONS

6% GREATER THAN COMPETITORS [14.2 N]

EXTRA TRAIL TRACTION TESTING

AVG. WEAR TESTER PERCEPTIONS



TOTALIS TRAIL TRACTION

PEGASUS TRAIL 3 TRACTION

ATHLETE & EXPERT VALIDATION

"INTEGRATING SHEAR SENSORS INTO TRAINING FOOTWEAR CAN PROVIDE A DATA-DRIVEN APPROACH TO IMPROVE ATHLETIC PERFORMANCE."
- MICHAEL MCGEEHAN, U.O., BIOMECHANICS & ENGINEERING

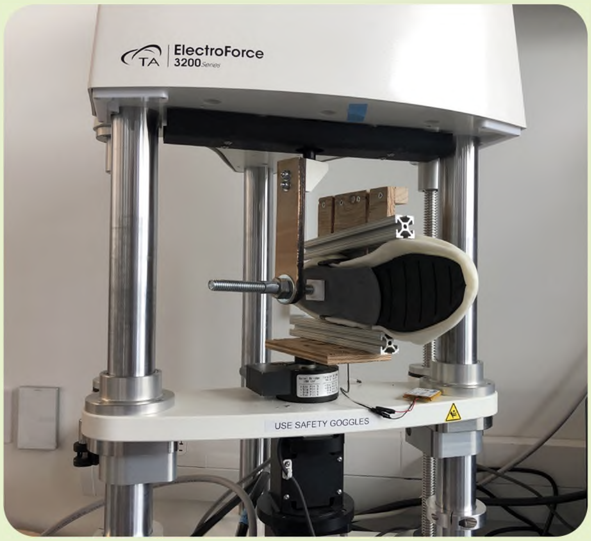
	TRACTION	OVERALL*
	8.0 /10	7.0 /10
	7.0 /10	6.9 /10
	9.0 /10	7.3 /10
	8.5 /10	7.5 /10

100% OF WEAR TESTERS SAID THE ACTIVO-ARCH TECHNOLOGY PROVIDES **EXTRA SUPPORT & LOCKDOWN**

"THE SPLIT DESIGN WILL HELP FIT VARIOUS FOOT SHAPES. I THINK THIS WILL IMPROVE LOCKDOWN & HELP ATHLETES FEEL MORE SUPPORTED."
- EVAN DAY, BROOKS RUNNING, RESEARCH SCIENTIST

SENSOR TESTING & VA

MECHANICAL TESTING

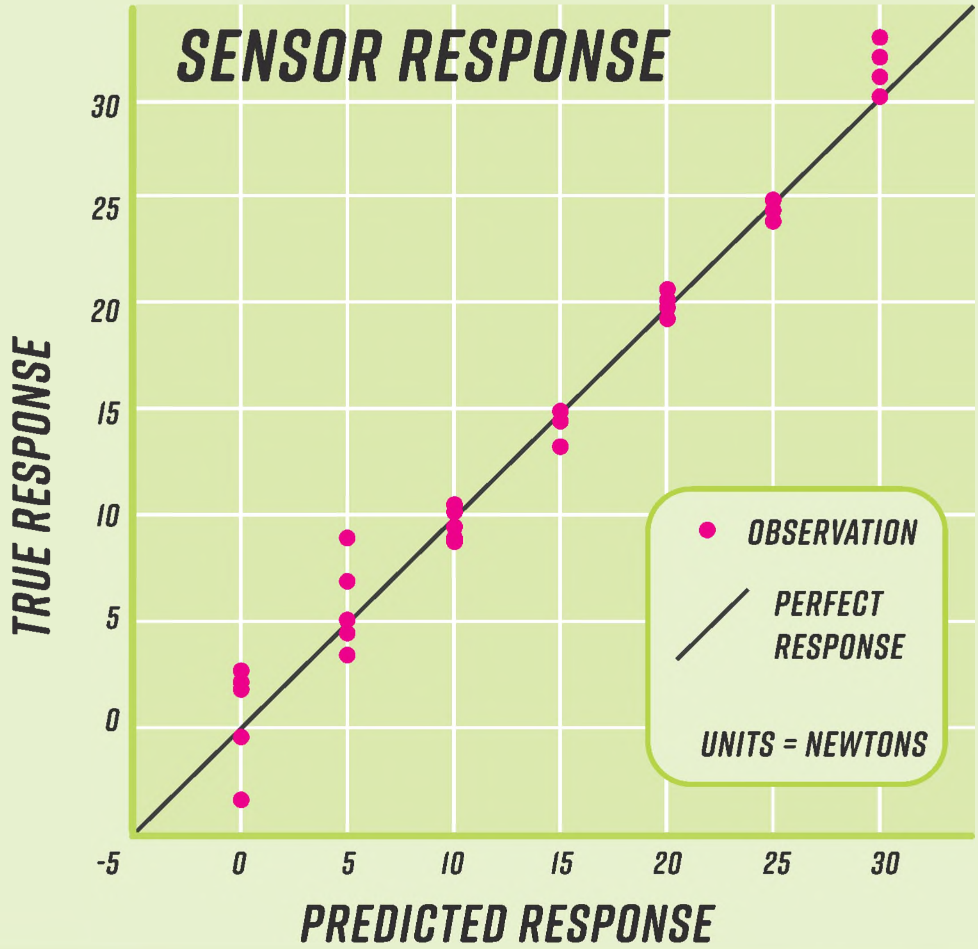


R-SQUARED VALUE

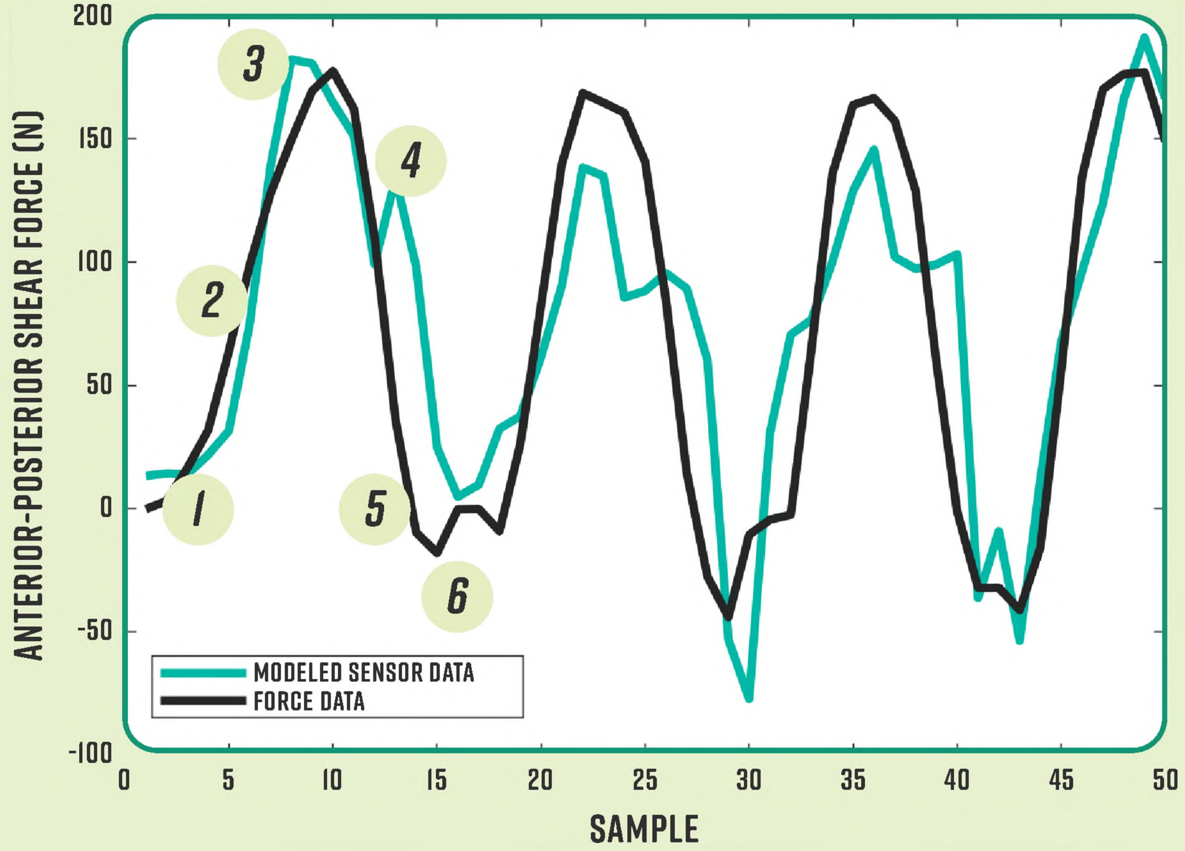
0.98

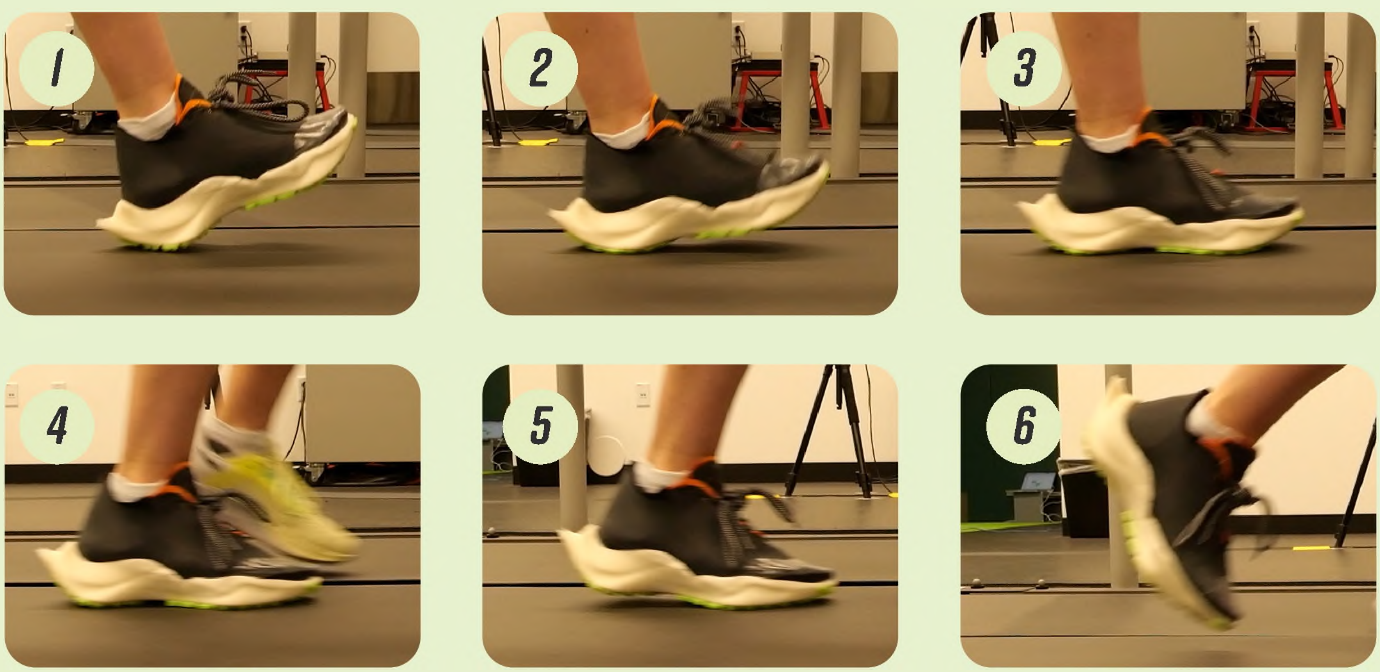
RMS

>5% ACCEPTABLE % ERROR FROM TARGET [1.0 RMS]



FORCE PLATE WEAR TESTING



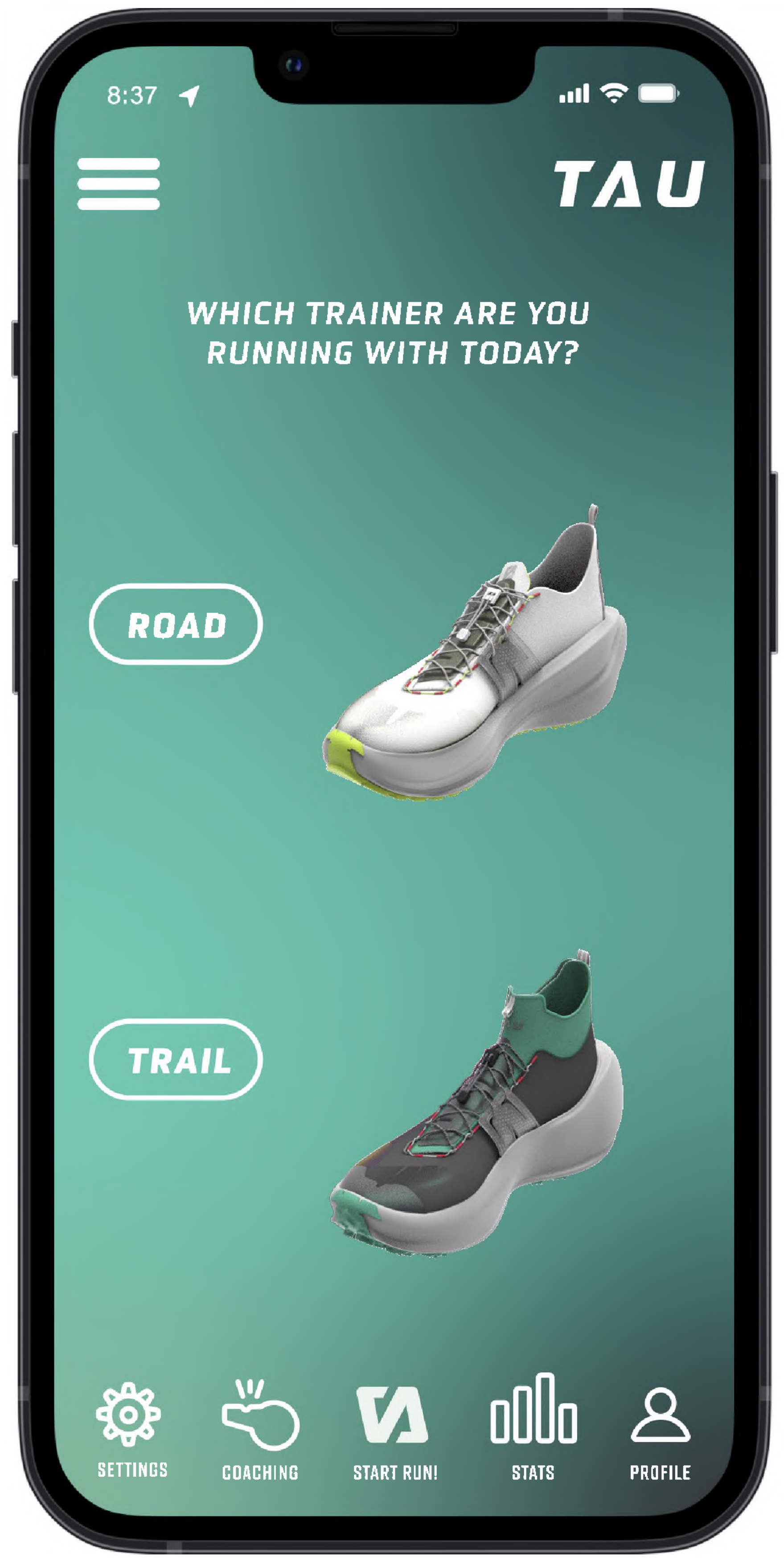


CONCLUSION

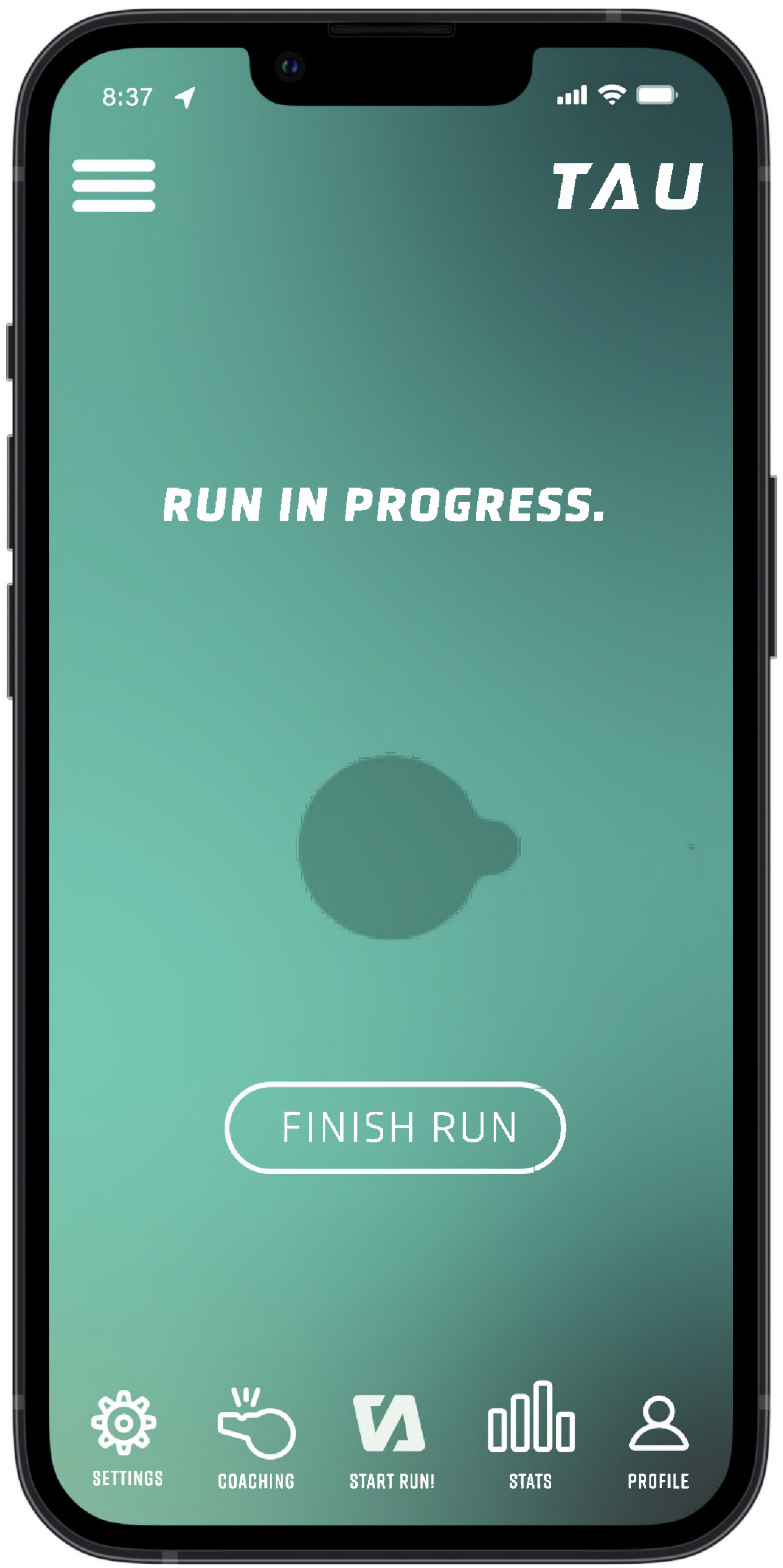
OVERALL BENEFIT, APP, MENTORS, ETC.

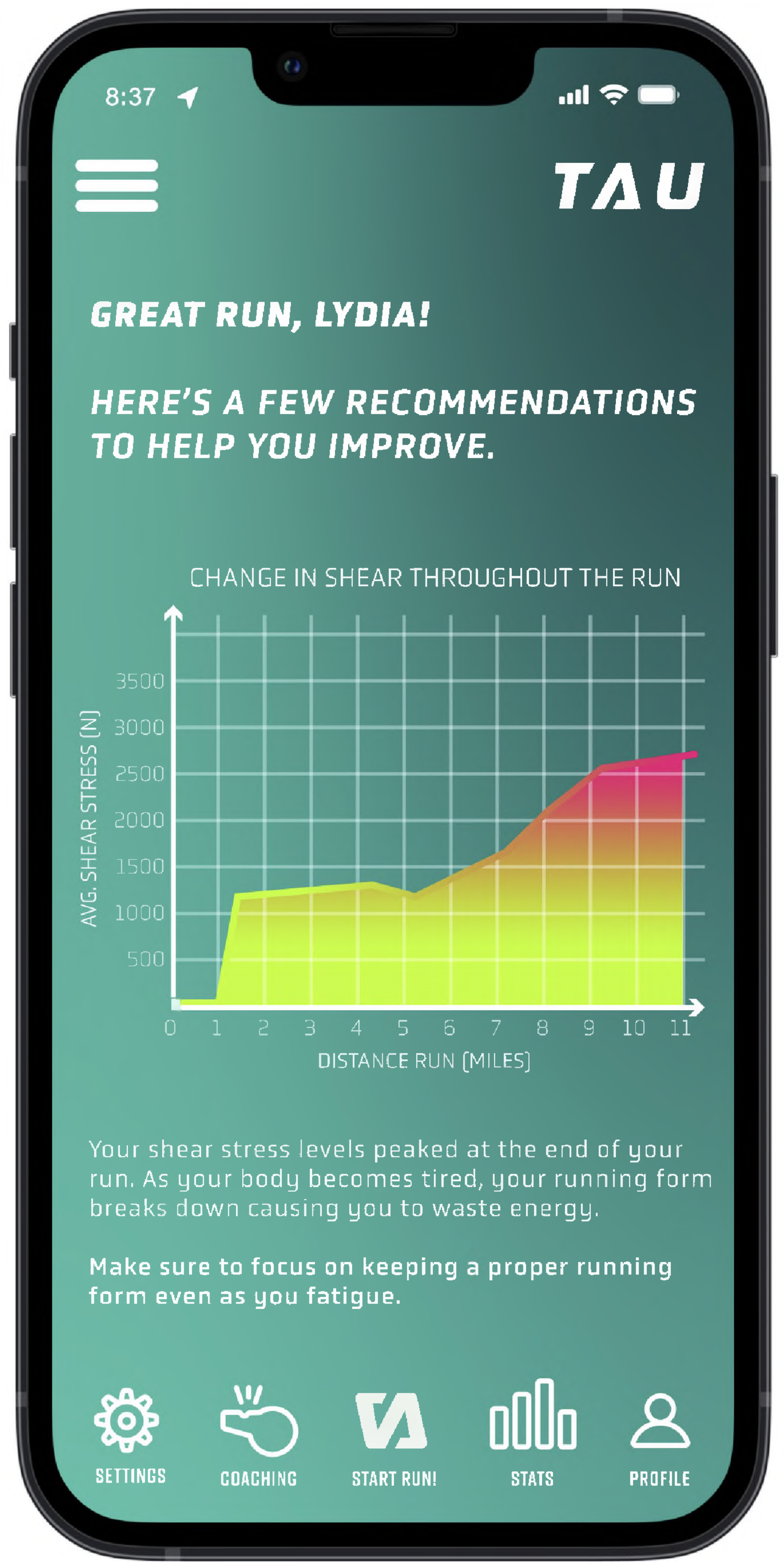

REAL-TIME FEEDBACK OF SHEAR FORCES AT THE FOOT-SHOE INTERFACE PROVIDES ATHLETES WITH A DATA-DRIVEN APPROACH TO IMPROVE PERFORMANCE

INTERACTING WITH THE APP



INTERACTING WITH THE APP





SENSOR DEVELOPMENT TEAM

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MICHAEL MCGEEHAN

ELECTRICAL ENGINEERING
KNIGHT CAMPUS

GHEE KEAT ONG

ADVISORS & MENTORS

SPORTS PRODUCT DESIGN
WHITE STAG

SUSAN SOKOLOWSKI

BIOMECH. RESEARCH SCIENTIST
BROOKS RUNNING

EVAN DAY

PRODUCT DESIGN
UO EUGENE

KIERSTEN MUENCHINGER

MEDIA & MODELS

PHOTO & VIDEO

DAVID GREEN

TRAIL MODEL

LYDIA POVOLNY

ROAD MODEL

LILIE MATIA

THANK YOU

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Appendix

SWOT Analysis

State-of-the-Art Trail Running Footwear:

PEREGRINE 11 → $ 120

SAUCONY

	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
UPPER	– Simplified mesh upper for increased ventilation – Strategically placed overlays for abrasion resistance – Includes a flexible, molded heel cup – Stable & secure upper with mid-foot internal straps	– Does not include weather-proof finishes – Could be more aesthetically pleasing	– Addition of weather-proofing for spring running – Improve the aesthetics	– There is a Gore-Tex version of the shoe, but it is less breathable
INSOLE	– Inexpensive – Fits the shoe interior well	– Not anti-microbial or odor resistant	– Addition of anti-odor or sweat wicking technology – Insoles contoured to the unique foot morphology due to sex	– Increasing technology in the insole will increase price – Insoles are often overlooked & technology in this area is often viewed as unnecessary
MIDSOLE	– PWRRUN foam midsole with a top layer of PWRRUN+ for added cushioning at the footbed – Includes a nylon thread tightly woven rock plate to protect the foot	– Single density foam doesn't cater to the difference pressure needs of specific areas of the foot – No rocker technology – No carbon plate	– Addition of rocker technology, energy return foam or an energy plate	– Increasing technology in the midsole will increase price
OUTSOLE	– Substantial 4mm lugs excel on wet, mud, & soft ground to provide confident traction – PWRTRAC rubber compound is durable yet soft to create a tacky grip	– Is not built for a hyper-specific terrain – Will handle various terrains decently well, but nothing amazingly well	– Outsole could be designed for a specific terrain	– Designing for a specific terrain makes the shoe less all-around

Figure 25. SWOT Analysis for Saucony's Peregrine 11 (Liles, 2021; Peregrine 11, n.d.).

SPEEDGOAT 4 → $ 145

HOKA ONE ONE

	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
UPPER	– Seamless interior to avoid any rub points – Overlays across the midfoot to increase stability	– Very little toe bumper – Doesn't protect the sides of the foot well – Narrow toe box – Thin, unpadded tongue	– Addition of weather-proofing for spring running	– There are various weather-proof trail runners on the market; HOKA is not typically known for weather-proofing
INSOLE	– Inexpensive – Fits the shoe interior well	– Not anti-microbial or odor resistant	– Addition of anti-odor or sweat wicking technology – Insoles contoured to the unique foot morphology due to sex	– Increasing technology in the insole will increase price – Insoles are often overlooked & technology in this area is often viewed as unnecessary
MIDSOLE	– Maximum cushioning due to a thick, 32mm stack of EVA foam – Includes rocker technology	– No carbon fiber plate for rock protection or energy return	– Addition of energy return or rock protection energy plate	– Increasing technology in the midsole will increase price
OUTSOLE	– Vibram Megagrip outsole with 5mm lugs provides a strong grip – Soft, sticky rubber material	– Mud cakes onto the traction pattern eliminating the grip	– Anti-clogging technology to avoid collecting mud and debris in the tread	– This technology has been developed for cleats so there could be patent infringement

Figure 26. SWOT Analysis for HOKA's SpeedGoat 4 (HOKA ONE ONE® Speedgoat 4 for Men | HOKA ONE ONE®, n.d.; Hoka Speedgoat 4 Review, n.d.).

FLIGHT VECTIV → $199

THE NORTH FACE

	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
UPPER	– Thick toe guard – Variable stiffness heel counter to provide stability at the heel and flexibility near the Achilles – Durable midfoot reinforcements – Includes Kevlar weather-proofing	– Stability is lacking – Padding is lacking so the laces bite into the foot	– Increase lock down – Improve colorways to withstand dirt & grime that is bound to be encountered on the trail	– The upper currently looks very clean & various changes are bound to affect the aesthetics, maybe negatively
INSOLE	– Inexpensive – Fits the shoe interior well	– Not anti-microbial or odor resistant	– Addition of anti-odor or sweat wicking technology – Insoles contoured to the unique foot morphology due to sex	– Increasing technology in the insole will increase price – Insoles are often overlooked & technology in this area is often viewed as unnecessary
MIDSOLE	– Includes a full-length carbon fiber plate for energy return that has a heel cup to add stability – Features rocker technology – Dual-density foam for a firm rearfoot and soft forefoot	– Midfoot bump hits in a different spot than expected so the runner has to retrain their gait to be quicker to their forefoot	– The carbon fiber plate could be changed to other materials and shapes	– The North Face Vectiv Infinite has a PEBAX plate & the Vectiv Enduris has a TPU plate
OUTSOLE	– SURFACECTRL 3.5mm lugs offer decent grip without slowing the athlete down	– Traction pattern leaves something to be desired – Outsole leaves some midsole foam unprotected	– Create a zoned traction pattern to attack every aspect of the trail	– The trail is unpredictable so zoning the traction may not be reliable

Figure 27. SWOT Analysis of North Face’s Flight VECTIV (FAAOMPT, n.d.; Men’s Flight VECTIV™ Trail Shoe | The North Face, n.d.; Shoe Review, n.d.; Winebaum, n.d.).

State-of-the-Art Trail Running Footwear:

ENDORPHIN 2 SPEED → $160

SAUCONY

	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
UPPER	– Comfortable mono-mesh upper that promotes breathability – Non-slip laces with improved lock down through throat geometry	– Stability could be improved – Aesthetics "look like a Twin Peaks fever dream" – Narrow toe box causes toes to feel crammed	– Addition of DWR finish for wet, spring weather – Applying additional overlays to increase stability & lockdown – Vastly improve the aesthetics	– Applying overlays will most likely impact the breathability of the upper – The aesthetics of the upper should not distract from the sensor technology
INSOLE	– Inexpensive – Fits the shoe interior well	– Not anti-microbial or odor resistant	– Addition of anti-odor or sweat wicking technology – Insoles contoured to the unique foot morphology due to sex	– Increasing technology in the insole will increase price – Insoles are often overlooked & technology in this area is often viewed as unnecessary
MIDSOLE	– PWRRUN PB midsole with embedded S-shaped, full-length nylon plate provides comfort, impact attenuation, & solid energy return – SpeedRoll rocker technology helps the foot move through the proper biomechanical gait	– Exposure at the outsole can cause the midsole to wear down or be damaged by debris	– The midsole is a great all-in-one midsole, but could be specialized for a certain distance or pace	– Specializing the midsole will take away the advantage of a shoe that works well for everything
OUTSOLE	– Visually-pleasing outsole design – Decent traction performance – Lightweight design	– XT-9000 rubber traction paper doesn't provide the necessary grip on wet surfaces – Outsole doesn't fully protect the foam midsole which can cause damage to the foam when running on a road that has debris	– Develop a full-length traction pattern that is designed specifically for heel-strikers	– A full-length traction pattern may add unnecessary weight

Figure 28. SWOT Analysis of Saucony's Endorphin 2 Speed ("Saucony Endorphin Speed 2 Performance Review » Believe in the Run," 2021; Saucony Endorphin Speed 2 Review, n.d.; SHOE REVIEW, 2021).

CLIFTON 8 → **$ 130**

HOKA ONE ONE

	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
UPPER	– Semi-gusseted tongue provides great support on the top of the foot & throughout the midfoot – Lace placement combined with the tongue design provides phenomenal lockdown	– Voluminous fit, too wide for narrow feet; needs improved lockdown & fit to work with various widths of feet – Breathability can be improved	– Improve the fit of the upper to allow for various foot widths – Increase the ventilation provided by the upper – Add a DWR finish in key areas to add weather-proofing	– Shoes are often offered in various widths (normal & wide) so changing the fit is most likely unnecessary
INSOLE	– Inexpensive – Fits the shoe interior well – 5mm thick for a plush, cushioned feel	– Not anti-microbial or odor resistant	– Addition of anti-odor or sweat wicking technology – Insoles contoured to the unique foot morphology due to sex	– Increasing technology in the insole will increase price – Insoles are often overlooked & technology in this area is often viewed as unnecessary
MIDSOLE	– 33.7mm stack of extremely soft EVA foam for an ultra-cushioned midsole – Rocker geometry for smooth-rolling transitions	– Built for slow runs, doesn't feel fast under foot – Originally stiff & requires break in	– Increase the "speediness" of the midsole – Include an energy plate within the midsole to improve energy return	– Increasing technology in the midsole will increase price
OUTSOLE	– Traction patches provide adequate grip on most surfaces	– The minimal outsole leaves much of the midsole exposed & vulnerable to damage by debris	– Create a full-length traction pattern to protect the midsole from debris	– A full-length traction pattern may add unnecessary weight

Figure 29. SWOT Analysis of HOKA's Clifton 8 (HOKA ONE ONE® Clifton 8 for Men | HOKA ONE ONE®, n.d.; Hoka One One Clifton 8 - Lab Review 2021 - From $130, n.d.).

AIR ZOOM PEGASUS 38 → $ 120

NIKE

	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
UPPER	– Upper uses a soft sandwich mesh with thick, looped eyelets that provide great lockdown without hot spots – Conforms well to the foot & provides stability	– Plush tongue padding & sandwich mesh trap heat & sweat – Narrow fit that doesn't work well for wider feet	– Reduce the layering of the upper to create better ventilation & breathability	– Reducing the layering of the upper will most likely reduce the comfort & stability of the upper
INSOLE	– Inexpensive – Fits the shoe interior well – Deep heel cup eliminates slippage	– Not anti-microbial or odor resistant	– Addition of anti-odor or sweat wicking technology – Insoles contoured to the unique foot morphology due to sex	– Increasing technology in the insole will increase price – Insoles are often overlooked & technology in this area is often viewed as unnecessary
MIDSOLE	– React foam midsole with forefoot air unit creates bouncy feeling	– Requires a break-in period to be comfortable	– Variable density cushioning to specifically cater to the individual cushioning needs for different areas of the foot – Full-length energy plate for a faster midsole	– Increasing technology in the midsole will increase price
OUTSOLE	– Made of hard-wearing, durable rubber that resists abrasion	– Traction is below average on wet surfaces due to the hard rubber outsole material	– Redesign the outsole & traction pattern to provide better grip on wet surfaces	– Creating an outsole designed specifically for wet surfaces may impact the performance of the outsole on dry surfaces as well as the durability of the outsole

Figure 30. SWOT Analysis of Nike's Air Zoom Pegasus 38 (Nike Air Zoom Pegasus 38 - Lab Review 2021 - From $105, n.d.; Petruny, 2021).

Questionnaire to Investigate Distance Runners' Appetite to Measure their Performance Metrics

Distance Running & Performance Metrics

Hello, my name is Gabi Lorenzo. I am currently a second-year student in the Sports Product Design Master's program at University of Oregon (anticipated graduation in June 2022). This survey is designed to collect research surrounding the desire to measure performance metrics by runners for my capstone thesis project. For my thesis project, I'm interested in engineering an innovative method of manufacturing performance training footwear for distance runners that integrates sensors to measure performance metrics into the shoe to analyze the foot-shoe interface.

If you have any questions regarding my thesis or would like to chat, you are welcome to reach out at glorenzo@uoregon.edu!

What is your gender? *

- ○ Male
- ○ Female
- ○ Non-binary
- ○ Prefer not to answer
- ○ Other: ______

What is your age? *

- ○ Under 16 years old
- ○ 16 to 20 years old
- ○ 21 to 25 years old
- ○ 26 to 30 years old
- ○ 31 to 35 years old
- ○ 36 to 40 years old
- ○ 41 to 45 years old
- ○ Over 45 years old

How many miles on average do you run per week for training purposes? *

Your answer ______

Do you track your performance metrics? *

- ◯ Yes
- ◯ No

Why do your track your performance metrics? *

Your answer

What tools do you use to manually track your performance metrics? (Select all that apply.) *

- ☐ I do not manually track my performance metrics
- ☐ Excel spreadsheet
- ☐ Notebook/diary/journal
- ☐ Other: ____________

What digital tools do you use to track your performance metrics? (Select all that apply.) *

- ☐ I do not use digital tools to track my performance metrics
- ☐ Smart watch
- ☐ Fitness tracker (non-watch)
- ☐ Heart rate monitor
- ☐ Pedometer
- ☐ Phone app
- ☐ Other: ____________

Which performance metrics are important to you? *

- [ ] Total miles run
- [ ] Total time of the run
- [ ] Pace time
- [ ] Cadence (how often your foot hits the ground)
- [ ] Ground contact time (how long is your foot on the ground with each stride)
- [ ] Vertical oscillation (how much your upper body moves up and down with each step)
- [ ] Stride length
- [ ] Heart rate
- [ ] Blood pressure
- [ ] VO2 max (the maximum volume of oxygen you consume per minute during intense training)
- [ ] Lactate threshold (the level when your body begins to accumulate lactic acid faster than you can flush it out)
- [ ] Other

Please rank the performance metrics that are important to you, from most important to least important. [E.g. If you selected "Total Miles Run," "Pace Time," and "Heart Rate;" and "Total Miles Run" is least important to you, and "Heart Rate" is the most important to you. Then your response would be: "Heart Rate, Pace Time, Total Miles Run."] *

Your answer

Would you be interested in a smart training shoe that could measure additional performance metrics at the interface between the foot, the shoe, and the ground? *

- ○ Yes
- ○ No

Do you have any concerns about smart training shoes? If yes, please describe your concerns? *

Your answer

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

FILED VIA ELECTRONIC FILING
SYSTEMCOMMISSIONER FOR PATENTS

PROVISIONAL APPLICATION COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT

under 37

C.F.R. § 1.53(c).

TITLE: SHEAR STRESS SENSOR

Inventors/Applicants:

Last	First	MI	City, State or City, Foreign Country
Ong	Keat	G.	Eugene, OR
McGeehan	Michael		Eugene, OR

Submitted herewith are:

☒ 26 pages of
☒ specification19 sheet(s)
☒ of drawings Application
Data Sheet

FEE CALCULATION

												Rate		Fee
Basic Filing Fee														$150.00
Total no.of pages	45	Multiplied by 75% for EFS	=	34	-	No. pages in	100	=	No. of extra pages, divided by 50, rounded	0	x	$210.00	=	$0.00

page discount	basic fee	up to nearest whole number	
TOTAL FILING FEE			**$150.00**

☒ Small entity status is claimed for this application.

☒ $150.00 is being submitted herewith via EFS to cover the above-listed fee(s).

☒ The Director is hereby authorized to charge any additional fees that may be required in connection with this filing, or credit over-payment, to Deposit Account No. 02-4550.

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Respectfully submitted,

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Registration No. 63,874

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	1505-106271-01
	Application Number	
Title of Invention	SHEAR STRESS SENSOR	

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
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☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Inventor Information:

Inventor 1 Remove

Legal Name

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	Keat	Ghee	Ong	

Residence Information (Select One) (●) US Residency ◯ Non US Residency ◯ Active US Military Service

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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	1505-106271-01
	Application Number	
Title of Invention	SHEAR STRESS SENSOR	

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Application Information:

Title of the Invention	SHEAR STRESS SENSOR		
Attorney Docket Number	1505-106271-01	**Small Entity Status Claimed**	☒
Application Type	Provisional		
Subject Matter	Utility		
Total Number of Drawing Sheets (if any)	19	**Suggested Figure for Publication (if any)**	

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application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must beprovided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by thisreference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

Application number of the previouslyfiled application	Filing date (YYYY-MM-DD)	Intellectual Property Authority or Country

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☐ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

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Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	1505-106271-01
	Application Number	
Title of Invention	SHEAR STRESS SENSOR	

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, 365(c), or 386(c) or indicate National Stage entry from a PCT application. Providing benefit claim information in the Application Data Sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.
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Prior Application Status		Remove	
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This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55. When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX)[i] the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(i)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

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Application Number	Country[i]	Filing Date (YYYY-MM-DD)	Access Code[i] (if applicable)

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Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

☐	This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013. NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	1505-106271-01
	Application Number	
Title of Invention	SHEAR STRESS SENSOR	

Authorization or Opt-Out of Authorization to Permit Access:

When this Application Data Sheet is properly signed and filed with the application, applicant has provided written authority to permit a participating foreign intellectual property (IP) office access to the instant application-as-filed (see paragraph A in subsection 1 below) and the European Patent Office (EPO) access to any search results from the instant application (see paragraph B in subsection 1 below).

Should applicant choose not to provide an authorization identified in subsection 1 below, applicant **must opt-out** of the authorization by checking the corresponding box A or B or both in subsection 2 below.

NOTE: This section of the Application Data Sheet is **ONLY** reviewed and processed with the **INITIAL** filing of an application. After the initial filing of an application, an Application Data Sheet cannot be used to provide or rescind authorization for access by a foreign IP office(s). Instead, Form PTO/SB/39 or PTO/SB/69 must be used as appropriate.

1. Authorization to Permit Access by a Foreign Intellectual Property Office(s)

A. Priority Document Exchange (PDX) - Unless box A in subsection 2 (opt-out of authorization) is checked, the undersigned hereby **grants the USPTO authority** to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the State Intellectual Property Office of the People's Republic of China (SIPO), the World Intellectual Property Organization (WIPO), and any other foreign intellectual property office participating with the USPTO in a bilateral or multilateral priority document exchange agreement in which a foreign application claiming priority to the instant patent application is filed, access to: (1) the instant patent application-as-filed and its related bibliographic data, (2) any foreign or domestic application to which priority or benefit is claimed by the instant application and its related bibliographic data, and (3) the date of filing of this Authorization. See 37 CFR 1.14(h)(1).

B. Search Results from U.S. Application to EPO - Unless box B in subsection 2 (opt-out of authorization) is checked, the undersigned hereby **grants the USPTO authority** to provide the EPO access to the bibliographic data and search results from the instant patent application when a European patent application claiming priority to the instant patent application is filed. See 37 CFR 1.14(h)(2).

The applicant is reminded that the EPO's Rule 141(1) EPC (European Patent Convention) requires applicants to submit a copy of search results from the instant application without delay in a European patent application that claims priority to the instant application.

☐ **2. Opt-Out of Authorizations to Permit Access by a Foreign Intellectual Property Office(s)**

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NOTE: Once the application has published or is otherwise publicly available, the USPTO may provide access to the application in accordance with 37 CFR 1.14.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	1505-106271-01
	Application Number	
Title of Invention	SHEAR STRESS SENSOR	

Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Applicant 1

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

Clear

○ Assignee	○ Legal Representative under 35 U.S.C. 117	○ Joint Inventor
◉ Person to whom the inventor is obligated to assign.	○ Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor:

If the Applicant is an Organization check here.	☒		
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Mailing Address Information For Applicant:			
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Address 2			
City	Eugene	**State/Province**	OR
Country	US	Postal Code	97403-1238
Phone Number		Fax Number	
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	1505-106271-01
	Application Number	
Title of Invention	SHEAR STRESS SENSOR	

Assignee 1

Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication. An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.

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Signature:

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This Application Data Sheet **must** be signed by a patent practitioner if one or more of the applicants is a **juristic entity** (e.g., corporation or association). If the applicant is two or more joint inventors, this form must be signed by a patent practitioner, **all** joint inventors who are the applicant, or one or more joint inventor-applicants who have been given power of attorney (e.g., see USPTO Form PTO/AIA/81) on behalf of **all** joint inventor-applicants.

See 37 CFR 1.4(d) for the manner of making signatures and certifications.

Signature	/Ethan A. McGrath/			Date (YYYY-MM-DD)	2021-04-08
First Name	Ethan	Last Name	McGrath	Registration Number	63,874

Additional Signature may be generated within this form by selecting the Add button.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	1505-106271-01
	Application Number	
Title of Invention	SHEAR STRESS SENSOR	

SHEAR STRESS SENSOR

FIELD

The field is shear sensing.

BACKGROUND

Use of prostheses can improve mobility, health, and quality of life; however, short and long-term variation in residual limb volume and shape can compromise the integrity of the residual limb-prosthetic socket interface, even for sockets that initially fit optimally. Sub-optimal socket fit exposes the residual limb to elevated localized shear stresses, which can macerate tissue giving rise to skin ulceration and pain. These conditions can lead to mobility deficits, prosthesis disuse, and reduced quality of life. Thus, there is a need for non-invasive sensors capable of measuring shear stresses occurring at the prosthetic socket and residual limb interface.

Other types of shear stress sensors for this application have been developed previously. However, many previous designs were based on capacitive sensing principles, which often necessitate bulky packaging and are sensitive to electromagnetic interface from the human body and surrounding environment. Such designs also typically require modifications to the prosthetic socket to accommodate bulky housing, wires, and power supplies. Another drawback to many previous designs for in-socket shear sensors is the inability to measure stress in more than one direction. Prohibiting measurement of the resultant stress can make the sensors extremely sensitive to placement and orientation errors, or increase bulk, complexity, or require numerous sensor units to achieve sensing of different shear axes. Accordingly, a need remains for improved shear stress sensors and related techniques that can address the drawbacks of existing sensors.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A-1E are perspective views of an example arrangement of sensor components.

FIGS. 2A-2D are illustrative examples of sensing principles, showing contactless opto-electronics sensor (left), and schematic of shear sensing principles based on optical coupling between a red, green, and blue light-emitting diode and photoresistor (right).

FIG. 3 is an example circuit diagram for controlling the operation of the optical sensors. **MCU**: Microcontroller Unit, **DAQ**: Data Acquisition system, **PWR**: Power, **I/O**: Input/Output.

FIG. 4A is a perspective view of a contactless optoelectronic shear sensor. FIG. 4B are plan view schematics of shear sensing principles based on optical coupling between the RGB LED and photoresistor. FIG. 5A is a side view of an example sensor architecture. FIG. 5B are images of a disassembled sensor (left), sensor without elastomerlayer (right), and fully-assembled sensor and circuitry (bottom). FIGS. 6A-6B are graphs of performance of a sensor example compared to High Accuracy Displacement Sensor (HADS), measuring horizonal (FIG. 6A) and vertical (FIG. 6B) displacements.

FIGS. 7A-7B are graphs of performance of a sensor example compared to the load cell, measuring horizonal (FIG. 7A) and vertical (FIG. 7B) shear stresses.

FIG. 8 is a graph of hysteresis response for an example sensor measured via HADS and load cell. FIGS. 9A-9B shows a schematic series of a sensor under no load and a deformable load. FIG. 10 is a flowchart of an example method of measuring shear characteristicsof two shearing bodies.

FIGS. 11A-11B are perspective views of an example shear stress sensor. FIGS. 12A-12E are gradient-based gray-scale spatially variable reflectance patterns. FIGS. 13A-13E are gradient-based color spatially variable reflectance patterns.FIG. 14 is an example linear gray-scale pattern.

DETAILED DESCRIPTION

Examples of the disclosed technology can be used in numerous application for shear stress sensing. Numerous disclosed examples sense shear stress based on optical coupling of reflected light. Selected examples can include contactless sensors for measuring shear stresses based on coupling of red, green, and blue light intensities. For example, color intensity of reflected light changes based on shearing between two bodies, which alters the visible color components of a surface having a colored grid. Shear stress can be calculated based on the intensity of light reflected by the various color(s) showing. Further examples can use changes in gray scale. Representative examples include a light source, light sensor, deformable transducer layer, and color grid for reflecting light, with parts coupled between first and second shearing bodies.

Sensor examples can have low power requirements and a small footprint, providing suitability for measuring shear stress in constrained environments. Example sensors can measure shear stress based on variations in light intensity, including using optical wavelength color reflectance variations or other reflectance variations, based on shearing of a surface with a reflecting pattern grid (such as a color or gray-scale pattern) with respect to a surface with a transparent window or window pattern.

Some example sensors can measure shear stresses along two perpendicular axes based on optical coupling between an optical source (e.g., a red, green, and blue light-emitting diode) and an optical detector (e.g., a photoresistor). Example sensors can enable measurement of interfacial shear stresses between two structures where shear strains appear. Selected applications can include monitoring of interfacial shear stresses between a residual limb and prosthetic socket. Additional applications in the medical space can include monitoring foot plantar tissue health in individuals with diabetic peripheral neuropathy and/or vascular dysfunction, or other scenarios requiring a contactless sensor with low power requirements and a small footprint.

Opto-electronics based sensing techniques are used to advantageously measure shear stress using thin and flexible housing packages, requiring minimal power, while being relatively unaffected by electromagnetism or normal force magnitude. Some disclosed sensor examples can be contactless, have a small footprint, remain unaffected by electromagnetic fields, and be able to measure shear stresses across a continuous range of orientations. In some examples that may be particularly advantageous in prosthetic arrangements, sensors can be integrated within current prosthetic socket systems without requiring substantial modifications or retrofits to that system, such as drilled holes to house sensors or port wires.

Introduction to Sensor Technology

The utility of tactile shear sensors is increasing rapidly, particularly for robotics, medical, geological, and orthopedic applications. Within the field of robotics, shear sensors are useful for detecting slippage in grasping devices or ground contact dynamics in walking devices. Among the many medical and orthopedic applications, measuring interfacial shear stresses between a residual limb and prosthetic socket can be used to manage socket fit and residual limb tissue health. Measuring shearing between a foot sole and shoe can be used to measure performance in athletes or to manage tissue ulceration among individuals with diabetic neuropathy and/or dysvascular conditions. Example disclosed sensors can be configured to satisfy the various design constraints associated with these applications, including by having a small footprint and flexible housings thereby making the sensors discreet or mechanically imperceptible to the user. Further, disclosed sensors can also be very light weight, have low power requirements, and be relatively unaffected by motion artifacts, normal force, or electromagnetic fields.

As discussed above, many existing shear sensors are based on capacitive sensing principles, which often necessitate bulky packaging and are sensitive to electromagnetic interference from the environment, nearby mechatronic systems, or human body. For example, Sanders and Daly (1993) used metal-foil strain gauges embedded in the wall of a prosthetic socket to measure residual limb-prosthetic socket interfacial shear stresses. However, the bulk and mass of these sensors necessitated that holes be cut in the wall of socket, thus limiting their usefulness in clinical or daily use settings. Cheng et al. (2010) developed a polymer-based capacitive sensing array for normal and shear force measurement in robotics and orthopedics. This design is more flexible but has a larger footprint than the metal-foil strain gauges. It also offers a relatively limited shear sensing capacity (< 1 N), making it unsuitable for many robotic and orthopedic applications. Laszczak et al. (2015, 2016) developed a 3D-printed capacitive shear stress sensor. This sensor has a miniaturized design (20×20×4 mm), but is unable todifferentiate between shear stresses along different axes.

In contrast to capacitive designs, optoelectronics-based sensors can be advantageous for measuring shear stress because they can be made thin, require minimal power, and be relatively unaffected by magnitude of normal force. Furthermore, devices based on optical sensing principles are generally unaffected by electromagnetic interference induced by the surroundings, human body, or other devices interacting with the sensor. Missinne et al. developed and validated a thin optical tactile shear sensor that senses shear stress based on optical coupling between a vertical-cavity surface-emitting later (VCSEL) and a photodiode, separated by a transparent elastomeric transducer layer. The sensor exhibited a repeatable sigmoidal relationship between photodiode current and shear stress for stresses up to 5 N. However, the device had a limited range of shear sensing, required high power to drive the VCSEL, and was generally unable to measure directionality of shear stresses, thereby limiting its usefulness for robotics, medical, and orthopedic applications.

As will be discussed further hereinbelow, disclosed optical-based shear stress sensors can be miniaturized with a scalable design that can be tuned to sense shearing of different magnitudes, including larger than 5 N. Some disclosed examples can also be configured to differentiate directionality of the shear stresses and require low power. Disclosed sensors can be fabricated using a simple, low-cost, optoelectronic sensor based designs for measuring uni-axial or multi-axial shear stresses.

Examples of the Disclosed Technology

An example of a shear sensor 100 is depicted in FIGS. 1A-1E. The sensor 100 includes a structural housing 102 for supporting a light source 104 (e.g., a red, green, and blue light emitting diode is depicted) and a photoresistor 106 for sensing resistance changes based on changes in light intensity. A transparent elastomer transducer layer 108 separates the sensor housing 102 from a base plate 110 having a spatially variable reflectance pattern, such as a color pattern grid 112 printed on the adjacent surface 114. Other examples can include gray scale patterns. Some pattern examples can be arranged linearly. The color pattern grid 112 forms a two-dimensional pattern. The design can be contactless, in that the sensor 100 can be configured such that sensor does not require contact or adhesion with both shearing bodies or can be configured such that all electronics and wiring can be placed on one side of the sensor. Leads 116 from the light source 104 and leads 117 from the photoresistor 106 can be coupled to separate electronic circuitry (not shown) including one or more processors, e.g., in a microcontroller unit, to control generation and timing of light emitted by the light source 104, and the detection of light by the photoresistor 106.

In various examples, the sensor housing 102 or the photoresistor 106 fixedly arranged relative to the transparent elastomer layer 108 displaces relative to the base plate 110 during a shear event, using the deformability of the transparent elastomer layer 108. The light emitted from the light source 104 can be directed through the transparent layer 108 or it can be transmitted through another medium including free space. In some examples, the base plate 110 can be attached to the layer 108, e.g., at the surface 114, and another surface 118 of the base plate 110 can provide a surface through which shear force is transmitted with an adjacent shearing body. In this way, the sensor 100 can form a unit that can be attached to one of the two shearing bodies without being attached to the other. In further examples, the base plate 110 can be attached to one of the two shearing bodies and the sensor housing 102 with transparent elastomer layer 108 can be attached to the other of the two shearing bodies. An interface between the layer 108 and the surface 114 of the base plate 110 can provide the surface through which shear force is transmitted between the two shearing bodies. In selected examples, the base plate 110 could be replaced by another body to fit a variety of sensing needs, including an existing surface of the other of the two shearing bodies. In a particular example, the sensor housing 102 could be embedded within a prosthetic socket and the base plate 110 could be replaced by a residual limb with the pattern 112 printed or placed thereon. FIGS. 1B-1E show various exploded and perspective views of the sensor 100.

Various disclosed sensor examples can use sensing principles depicted in the example sensor 200 shown in FIGS. 2A-2D. The sensor 200 includes a light source 202 and an optical detector such as a photoresistor 204 in a fixed arrangement with respect to each other, e.g., coupled to a sensor housing 206. The sensor housing 206 is typically attached to a first shearing body. The sensor 200 can measure shear stress based on changes in optical coupling between the light source 202 (e.g., red, green, and blue light-emitting diode) and the photoresistor 204 and the variation in detected reflectance. A body 208 (e.g., a base plate or an adjacent second shearing body) is situated adjacent to the sensor housing 206 and includes a surface 210 having a colored grid 212 of red 213a, green 213b, blue 231c, and magenta 213d (blue + red) squares. For example, the pattern can include a square of a first color (e.g., green), squares of a second color (e.g., red) on opposite sides of the square of the first color along a first axis (e.g., vertical), squares of a third color (e.g., blue) on opposite sides of the square of the first color along a second axis (e.g., horizontal), and squares of a fourth color (e.g., magenta) at corner positions relative to the square of the first color. In some examples, such as shown in FIG. 2B, the color pattern can repeat.

The housing 206 and the body 208 can be separated by a transparent elastomer transducer layer 214. A surface 216 opposing the surface 210 can be defined by the sensor housing 206, layer 214, and/or window pattern 218 of a window 219, such as an aperture mask situated adjacent the photoresistor 204. In representative examples, a light beam 220 is emitted from the light source 202 and directed through the transparent elastomer transducer layer 214 to the surface 210. A reflected beam 222 is directed back through the layer 214 to be received through the window pattern 218 by the photoresistor 204. The aperture mask can include one or more aperture regions 224 that allow some of the reflected beam 222 to be received for detection by the photoresistor 204 or other optical detector. In further examples, one or both of the transmissions through the layer 214 can be through free-space or another material. In some examples, lens, mirrors, or other optical coupling components can be present to focus, direct, or couple the light beam 220 directed to the surface 210, e.g., adjacent to the light source 202, or to collect the reflected light 220 reflected by the colored grid 212, e.g., adjacent to the photoresistor 204 or window 219. Control circuitry is coupled to the light source202 to repetitively cycle the color of the LED (red, green, and blue), while measuring the reflected light intensity as a resistance change at the photoresistor 204 during red (R_r), green (R_g) and blue (R_b) light illumination.

Referring to FIG. 2D, when there is no shear force between the first and second bodies, surfaces 210 and 216 are perfectly aligned with the green squares 213b and only green appears in the window. Thus, the sensor 200 will only measure a resistance change during green light, and no resistance change during blue or red light since there is no blue or red color to reflect the light ($R_g > 0$, $R_r = R_b = 0$). When a vertical shear force is present between the first and second bodies, surfaces 210 and 216 will be misaligned and the red squares 213a on the surface 210 pattern 212 will show through surface 216, leading to changes for R_g and R_r. In representative examples, the values of R_g and R_r are inversely proportional and proportional to the vertical shear force, respectively. As a result, vertical shear force can be calculated as the ratio R_r / R_g, and horizontal shear force can be determined as R_b / R_g. In some examples, an amplified circuit and analog-to-digital converter are coupled to the photoresistor to convert an analog output signal in the form of a variable resistance into a digital signal for processing.

FIG. 3 is example control circuitry 300 coupling different sensor components. It will be appreciated that numerous other sensor circuit configurations are possible and may enhance, optimize, or expand disclosed examples. The control circuitry 300 includes a microcontroller (MCU)/data acquisition (DAQ) unit 302, which can be configured to control the color and duty cycle of a common anode RGB LED 304 by controlling power to input/output pins. The MCU/DAQ 302 also can be coupled to a photoresistor 306 and measures resistance changes from the photoresistor 306, which can be translated into changes in magnitude and direction of shear stress. An example signal amplifier 308 can also be coupled to the photoresistor, which could be used to improve the ability to detect small changes in resistance. Other components can be included or removed in various examples to adjust measurement accuracy or tailor the circuit to the type of optical detector. For example, voltage dividers, wheatstone bridges, pull-down resistors, etc., can be used. In some examples, additional communication circuitry can be provided, such as wireless Bluetooth, WiFi, or other wireless modules, for communicating measurement data with a separate computing device, such as a computer, hand-held device, wearable computing device, etc.

Another example sensor 400 is shown in operation in FIGS. 4A-4B. Example sensors can be configured with two-dimensional reflective pattern arrangements, such as colored grid pattern 402, so that multi-axial shear stress measurements can be performed. One-dimensional reflective pattern arrangements can be used in some examples as well, including gray-scale based or color-based. Reflectance variations are produced based on optical coupling between an optical detector, such as a photoresistor, and an optical light source, such as a red, green, and blue (RGB) light-emitting diode (LED). Other suitable optical detectors can include photodiodes, phototransistors, pixelated arrays, etc. However, photoresistors can be advantageous for their simplicity, low-cost, and small footprint. Suitable optical detectors can convert light intensity into an electrical signal, including resistance signals, voltage signals, current signals, etc. Contactless configurations can include all electronics and wiring at one side of the sensor, e.g., adjacent to the optical detector and/or optical source. The instrumented side of the sensor has a windowed pattern defined by a surface, e.g., Surface A, whereas an opposing side of the sensor displays the colored grid pattern 402 consisting of green, red, blue, and magenta (red + blue) squares on an opposing surface B. Other colors may be used in some examples. In some examples, the pattern on Surface B could be printed on a second sensor component or on an adjacent stationary surface or existing device (e.g., a shearing body on a robot). Controlling electronics cycle the LED color to produce emitted light 404 while measuring the intensity of reflected light 406 as a resistance change at the photoresistor during red (R_r), green (R_g), and blue (R_b) light illumination. The portion of the emitted light 404 that is reflected by the Surface B to become reflected light 406 can be determined by the color of the emitted light and the color of the surface that reflects the light. Because shear causes displacement of the colored grid pattern 402 relative to the windowed pattern, the amount of light that is reflected and received by the photoresistor varies according to the displacement andspatial reflectance characteristics of the colored grid pattern 402.

When there is no shear force applied to the sensor, Surfaces A and B are perfectly aligned, and thus only green appears in the window on Surface A (FIG. 4A). Under these conditions, the photodiode only measures a resistance change when the LED is emitting green light, since there is no blue or red color to reflect the light ($R_g > 0$, $R_r = R_b = 0$). A vertical shear force causes a relative displacement producing a misalignment of Surfaces A and B, e.g., through a shear deformation of an intermediate elastomer layer, and the red squares on Surface B are exposed through the window of Surface A, leading to resistance changes in R_g and R_r. The values for R_g and R_r are inversely proportional and proportional to the magnitude of vertical shear force, respectively. Similarly, a horizonal shear force cause the blue on Surface B to be visible in the window on Surface A. As a result, vertical shear force can be calculated as the ratio R_r / R_g, and horizontal shear force can be determined as R_b / R_g.

However, perfect alignment at a nominal position and unloaded state such that reflectance from only a green square may be detected is not a requirement. For example, a misaligned position with two or more colors being detectable can be defined as a nominal position and displacements that produce variations in the detected resistances or other output signal values (e.g., voltage and/or current) can be used to determine uniaxial or multi-axial shear stresses. A calibration routine can be performed to assign detected resistance values under no shear load as a nominal or unloaded state. Over time the alignment of the pattern 402 relative to the optical detector can drift from a nominal state, e.g., due to slipping or wear. Such drift may be more likely in examples without rigid attachment between the color pattern 402 and a sensor housing or intermediate transparent layer. The calibration routine can be reperformed to reset the resistances detected that define an unloaded state. In some examples, the grid pattern 402 can be repeated (e.g., as shown in FIG. 2B) so that a displacement drift larger than the dimensions of the colored squares can be tolerated. For example, a the sensor can be electronically recalibrated without requiring replacement or the sensor or physical realignment of the sensor and grid pattern.

FIGS. 5A-5B show another example sensor 500 that includes an instrumented housing 502, an LED 504 supported by the housing, a photodiode 506 to operate as an optical detector, control circuitry 508 to drive the LED 504 and process the output signal from the photodiode 506, a color pattern arranged on an opposing surface such as a plate 510, and an intermediate optically clear deformable polydimethylsiloxane (PDMS) elastomer layer 512 (e.g., Sylcap, MicroLubrol, Clifton, NJ) separating opposing surfaces 514, 516. In the particular embodiment shown, the packaging for the sensor 500, including circuitry, is 15×15×5 mm. A thickness of the sensor 500, e.g., perpendicular to the shear displacement, can depend upon the thickness of the PDMS elastomer layer 512. The range of shear stress magnitudes and sensitivity to changes in shear stress can be tuned based on PDMS layer thickness and curing conditions, which affects the material properties.

In a particular example, the LED (e.g., DotStar APA102-2020, Shenzhen LED Color Opto Electronic Co., Shenzhen, China) is 2×2×0.9 mm and emits red, green, and blue light at 620, 520, and 465 nm wavelengths, respectively. At 20 mA, the brightness for these colors is 300-330, 420-460, and 160-180 mcd. The photodiode 506 (e.g.,Vishay Semiconductors, VEMD1060X01, Shelton, CT) is 1×2×0.9 mm with a 0.2 mm^2 active area. The photodiode 506 is sensitive to wavelengths ranging 350 – 1070 nm, which is inclusive of the red, green, and blue color spectra. The LED 504 and photodiode 506 are mounted to a printable circuit board (PCB) 518 (e.g., OshPark, Lake Oswego, OR) which can be housed in a 3D printed methylacrylate photopolymer resin 520. By employing rapid prototyping technology in the fabrication process, the cost- efficiency and versatility of the sensor 500 are improved. Within the housing 502, the LED 504 and photodiode 506 can be isolated such that photodiode 506 is only exposed to light reflected from surface 514 or exposure from other light is limited.

In an example fabrication method, a resin mold for the PDMS elastomer layer was 3D printed and adhered to a Teflon plate. The base agent and curing agent were poured into the mold and cured at room temperature for 24 hrs. After curing, the PDMS elastomer was removed from the mold trimmed to the dimensions of the sensor housing, and adhered to opposing surfaces 514, 516 of the sensor with an adhesive (e.g., Loctite

401). In a previous material characterization studies, the shear modulus of PDMS at room temperature was found to be 250 - 450 kPa. However, the material properties ofPDMS are tunable by adjusting the geometry and curing parameters of the elastomer.

In an experimental characterization of the sensor 500, sensor response to both displacement and applied shear force were measured. Measuring the response to displacement can characterize the baseline performance of the sensor components. Measuring the response to shear stress can characterize the sensor's performance under conditions for shear measurement applications. To apply controlled displacement, a 3D-printed housing was fabricated to secure the sensor components in a materials testing system (EnduraTEC ELF, TA Instruments, New Castle, DE). For displacement tests, a 3 mm-thick spacer was placed between the two sides of sensor in place of the elastomer. The instrumented side of the sensor 500 (e.g., surface 516) was displaced with respect to the surface 514 in 1 mm increments up to 10 mm. At each 1 mm position, a static measurement of RGB color intensity was recorded by cycling each LED color 10 times at 50 Hz and recording the average of the 10 measurements for each color. To measure the repeatability of the sensor 500, 5 trials were completed and inter-trial variability was calculated. Measurement results are depicted in FIG. 6A. Measurements were then repeated in the horizontal direction and the results are depicted in FIG. 6B. Sensor-derived measurements of displacement were then compared to measurements from the materials testing system's integrated High Accuracy Displacement Sensor (HADS) (EnduraTEC ELF, TA Instruments, New Castle, DE), with such results also shown in FIGS. 6A-6B.

To characterize the sensor's performance for measuring shear stress, a 3 mm-thick optically-clear PDMS elastomer layer was adhered between surfaces 514, 516. The sensor was then placed in the materials testing system using the methods described above. The materials testing system was actuated for loads ranging 0 – 20 N in 2.5 N increments, measured via a load cell (1516FQG-100, TA Instruments, New Castle, DE) placed in series with the actuator, with related results disclosed in FIGS. 7A-7B. Red, green, and blue color intensity was measured as a resistance at the photodiode during each static load increment. Each LED color was cycled 10 times at 50 Hz and the average resistance was recorded for each color. To measure the repeatability of the sensor, 5 trials were completed and inter-trial variability was calculated. Sensor- derived measurements of shear stress were then compared to data from the load cell.Hysteresis of the sensor was also characterized. All data were collected in dark conditions to avoid interference from ambient light sources.

Displacement data measured from the HADS (accuracy: ± 0.0001 mm) and load data from the in-series load cell (accuracy: ± 0.0001 N) were used as reference standard comparator values to model and characterize the sensor's performance. The ratio R_r / R_g was used to for sensing displacement/shear stress changes in the vertical direction, whereas R_b / R_g was used for sensing horizonal changes. For both displacement and shear stress, a model fit was derived for the sensor's response (i.e., light intensity) compared to the reference standard value.

Gaussian Process (GP) regression was used to model the sensor response for both the displacement and shear stress conditions (e.g., Mathworks, Natick, MA). Compared to traditional regression models, GPs can be advantageous for characterizing sensor performance because they can directly capture model uncertainty in addition to predicted values. Further, *a priori* knowledge and specifications can be added about the shape and behavior of the model by selecting different kernel functions (e.g., linear vs exponential). Five rounds of cross-validation were performed using randomized data partitions. The validation results were averaged across the rounds to provide an overall characterization of the model's predictive performance. Sensor performance was characterized using coefficient of determination (R^2), mean absolute error (MAE), and root-mean-squared error (RMSE) values across the full range of conditions tested.

Sensor-derived measurements of horizontal displacement matched HADS values well ($R^2 > 0.99$, MAE = 0.08 mm, RMSE = 0.20 mm). The sensor showed similar performance for vertical displacement ($R^2 > 0.99$, MAE = 0.07 mm, RMSE = 0.16 mm) (Figure 4). These data serve to demonstrate the baseline performance of the sensor's operating principle of measuring optical coupling between the RGB LED and photodiode based off light reflected from the patterned color surface. Inter-trial variability was < 0.02%, indicating that the sensor is capable of making repeatable measurements. Higher residuals (~ 1 mm) for displacements of 1 mm in both the horizontal and vertical directions indicate that the sensor may not be sensitive to displacements < 1 mm. This parameter may be tunable through sensor design modifications such as LED light intensity or use of an amplifier.

The sensor's performance for measuring shear stresses in the horizontal and vertical directions showed greater variability compared to displacement measurements. Nevertheless, sensor-derived measures of horizonal shear stress matched load cell data well ($R^2 > 0.96$, MAE = 0.97 N, RMSE = 1.2 N). Performance in the vertical directional was more accurate and exhibited decreased variability compared to the horizonal direction ($R^2 > 0.98$, MAE = 0.91 N, RMSE = 0.9 N).

The physical sensor package (i.e., resin housing and PDMS elastomer) showed a linear relationship between load and displacement ($R^2 > 0.99$) as measured via the load cell and HADS. Hysteresis response, as shown in FIG. 8, was less than 0.1% across the full range of loads and displacements. The relationship between force (F) and displacement (x) was 13.4 N/mm and the PDMS layer has a surface area (A) of 50 mm^2. As such, the shear modulus (G) of the sensor's PDMS can be calculated as function of force, displacement, and PDMS area (eq. 1), assuming rigidity of the resin housing:

$$G = \frac{F/x}{A} = \frac{13.4\,N/mm}{50\,mm^2} = 268\,kPa \quad \text{Eq (1)}$$

The calculated modulus of 268 kPa is similar to values reported in previous characterizations of the material properties of PDMS. The modulus of PDMS can also be tuned based on different curing parameters, which allows disclosed sensor examples to be scalable to meet different loading requirements. Values between 0.93 mPa and 450 kPa have been reported.

The linearity, scalability, and resolution in shear stress measurements derived from this sensor support its use for in robotics, medical, and orthopedic applications. High linearity is advantageous, as it can potentially allow for simplified sensor calibration and minimal signal conditioning requirements for signal processing. The scalability is also advantageous, as many previous shear sensor designs were limited in their applications due to low sensing range. High sensor resolution is important for a variety of uses. For example, sensor feedback could be used to allow a grasping robot to handle a fragile object by providing the necessary grip force to manipulate the object without breaking it. In medicine, pressure of < 8 kPa can cause tissue ischemia, thus necessitating high resolution for sensors tasked with identifying these conditions. Shear stress has been shown to be at least equivalent to pressure as an external factor leading to tissue breakdown, and thus, high resolution for shear measurements from this sensor show promise for providing early indication of tissue breakdown. Data show differentiation between horizonal and vertical shear stresses and show that the sensor performs equally well in both dimensions. This quality is especially advantageous compared to previous work in optical-based shear sensors which were only capable of sensing resultant shear stress. The ability to measure multi-axial shear stresses has typically been limited to use of strain gauges. Compared to this sensor, strain gauges are often larger (e.g., 47 mm), heavier (e.g., 375 g), require greater power, and necessitate being tethered by cables. FIGS. 9A-9B depicts shearing in an example shear sensor 900 attached to a primary shearing body 901. The sensor 900 shears between a sensor housing 902 and abody 904 having a spatially variable reflectance pattern affixed thereon, using the deformability of an intermediate deformable layer 906. The deformation of the layer 906 provides a relative displacement between the sensor housing 902 and body 904. Anoptical probe beam 908 emitted from an optical source 910 supported by the housing 902 can be directed to the body 904 and reflected back 911 to an optical detector 912 also supported by the housing 902. As the body 904 is displaced, the patten on the body904 displaces as the probe beam 908 continues to be directed in the same direction. The resulting light 911 detected by the optical detector varies according to the spatially variable reflectance pattern on the body 904. FIG. 10 shows an example method 1000 of determining a shear characteristic between two shearing bodies. At 1002 a light beam is directed to an opposing surfacehaving a spatially variable reflectance pattern. At 1004, the two shearing bodies are displaced with a shearing force. At 1006, a portion of the beam reflected by the opposing surface is detected, producing an output signal that has changed due to thedisplacement. At 1008, a shear characteristic, such as a shear stress, strain, or displacement, is determined based on the detected portion of reflected light.

FIGS. 11A-11B shows an example of a compact shear sensor 1100. The parts of the sensor 1100 include a base plate 1102 having a colored pattern, a transparent PDMS layer 1104, a sensor housing 1106 having a window, and a printed circuit board 1108 having a light source, light detector, and various arranged electrical components.

FIGS. 12A-12E shows five different gradient-based gray-scale patterns 1200A-1200E that can provide spatially varying reflectances. The pattern 1200A includes a radially symmetric gray-scale variation that can be used in some shear sensors. A white LED can be used with a photodiode to measure reflectance changes associated with shear displacement and stress/strain. The pattern 1200B includes a plurality of sub-patterns that can also each include radially symmetric gray-scale variations. In some examples, a plurality of photodiodes can be coupled each to a respective sub-pattern and a torsional measurement can be obtained based on the different detected variations in reflectance associated with a torsional displacement and stress. The patterns 1200C, 1200D show gradients in vertical and horizontal directions, respectively. In some examples, separate photodiodes can be coupled to respective vertical and horizontal patterns to produce linear displacement measurements based on detected reflectance variations. Pattern 1200E includes two perpendicular gradient variations that can be used to measure shear stress along perpendicular axes.

FIGS. 13A-13E shows five different gradient-based color patterns 1300A-1300E that can provide spatially varying reflectances. The color patterns 1300A-1300E include spectrally-based spatial variations, e.g., with a red center in pattern 1300A or in sub-patterns in pattern 1300B that vary to shorter wavelengths with increasing radial distance from the centers. Patterns 1300C, 1300D show similar spectral-spatial variations, from bottom to top (or vice versa) in pattern 1300C and from left to right (or vice versa) in pattern 1300D. Pattern 1300E includes two perpendicular gradient spectral-spatial variations, with red in a bottom left corner and decreasing in color wavelength with increasing vertical and increasing horizontal positions.

FIG. 14 is an example gray-scale pattern 1400 including a central square 1402 and opposite squares 1404a, 1404b. The central square 1402 is a selected gray-scale color, such as white, black, or an intermediate shade of gray. The opposite squares 1404a, 1404b are typically a common gray-scale color different from the gray-scale color of the central square 1402. The pattern 1400 can also be repeated in the linear direction shown or can be extended two-dimensionally, e.g., in both vertical and horizontal directions. In some examples, a separate optical detectors are coupled to different linear pattern arrangements and optically isolated from each other. In further examples, a common optical detector can be used, e.g., with an optical source arranged to illuminate the different linear patterns at different times and the linear pattern arrangements aligned with separate aperture windows.

General Considerations

As used in this application and in the claims, the singular forms “a,” “an,” and “the” include the plural forms unless the context clearly dictates otherwise. Additionally, the term “includes” means “comprises.” Further, the term “coupled” does not exclude the presence of intermediate elements between the coupled items.

The systems, apparatus, and methods described herein should not be construed as limiting in any way. Instead, the present disclosure is directed toward all novel and non-obvious features and aspects of the various disclosed embodiments, alone and in various combinations and sub-combinations with one another. The disclosed systems, methods, and apparatus are not limited to any specific aspect or feature or combinations thereof, nor do the disclosed systems, methods, and apparatus require that any one or more specific advantages be present or problems be solved. Any theories of operation are to facilitate explanation, but the disclosed systems, methods, and apparatus are not limited to such theories of operation.

Although the operations of some of the disclosed methods are described in a particular, sequential order for convenient presentation, it should be understood that this manner of description encompasses rearrangement, unless a particular ordering is required by specific language set forth below. For example, operations described sequentially may in some cases be rearranged or performed concurrently. Moreover, for the sake of simplicity, the attached figures may not show the various ways in whichthe disclosed systems, methods, and apparatus can be used in conjunction with other systems, methods, and apparatus. Additionally, the description sometimes uses terms like "produce" and "provide" to describe the disclosed methods. These terms are high-level abstractions of the actual operations that are performed. The actual operations that correspond to these terms will vary depending on the particular implementation and are readily discernible by one of ordinary skill in the art. In some examples, values, procedures, or apparatus' are referred to as "lowest", "best", "minimum," or the like. It will be appreciated that such descriptions are intended to indicate that a selection among many used functional alternatives can be made, and such selections need not be better, smaller, or otherwise preferable to other selections. As used herein, optical radiation or light beams refers to electromagnetic radiation at wavelengths of between about 100 nm and 10 µm, typically between about 200 nm and 2 µm, and more typically up to about 700 nm in color-based examples. Many disclosed examples use light emitting diodes, but other light sources can be suitable, including laser diodes, and other laser or light emission sources. In some examples, propagating optical radiation is referred to as one or more beams which can have diameters, shapes, cross-sectional areas, and beam divergences. Such beam parameters can depend on beam wavelength and the optical systems used for beam shaping, including lens arrangements, diffusers, or other optical components where suitable. For convenience, optical radiation is referred to as light in some examples and need not be at visible wavelengths. Reflectance generally refers to the ability of surfaces to reflect light differently and the proportion of light striking a surface which is reflected off the surface. The term "surface" is used in connection with relating optical components, and it will be appreciated surfaces can include various features, including edges, planes, threads, serrations, textures, chamfers, notches, detents, clamping members, etc., and such surfaces can be arranged in orientations other than parallel or perpendicular to different features of optical components where convenient.

There are several advantages to disclosed technology as compared to other shear sensors, including a) allowing differentiation of directional shear measurements, b) not requiring wire connections on both sides of the shearing bodies, c) since shear force is measured as the ratio of two resistances, calculated shear force can be independent of light intensity, thus the sensor can be misaligned up to 5 mm without impacting its performance, and d) relatively simple circuitry or electronic components can be used, making example sensors low-cost, robust, and easy to use.

Disclosed techniques may be, for example, embodied as software or firmware instructions carried out by a digital computer. For instance, any of the disclosed shear or displacement measurement techniques can be performed by a computer or other computing hardware (e.g., MCU, CPLD, ASIC, System-on-Chip, RISC, FPGA, etc.) that is part of a shear stress sensor or related measurement system. The shear sensor or measurement system can be programmed or configured to receive optical detector data associated with displacement of shearing bodies and perform the desired shear stress, strain, and/or displacement measurement computations (e.g., any of the measurement techniques disclosed herein). The computer can be a computer system comprising one or more processors (processing devices) and tangible, non-transitory computer-readable media (e.g., one or more optical media discs, volatile memory devices (such as DRAM or SRAM), or nonvolatile memory or storage devices (such as hard drives, NVRAM, and solid state drives (e.g., Flash drives)). The one or more processors can execute computer-executable instructions stored on one or more of the tangible, non-transitory computer-readable media, and thereby perform any of the disclosed techniques. For instance, software for performing any of the disclosed embodiments can be stored on the one or more volatile, non-transitory computer-readable media as computer-executable instructions, which when executed by the one or more processors, cause the one or more processors to perform any of the disclosed measurement techniques. The results of the computations can be stored (e.g., in a suitable data structure or lookup table) in the one or more tangible, non-transitory computer-readable storage media and/or can also be output to the user, for example, by communicating to a remote computing device, or by displaying, on a display device, shear stress, strain, and/ordisplacement values, changes, mappings, etc., with a graphical user interface.

In view of the many possible embodiments to which the principles of the disclosed technology may be applied, it should be recognized that the illustrated embodiments are only representative examples and should not be taken as limiting the scope of the disclosure. Alternatives specifically addressed in these sections are merely exemplary and do not constitute all possible alternatives to the embodiments described herein. For instance, various components of systems described herein may be combined in function and use. We therefore claim all that comes within the scope of the appended claims.

We claim:

1. A sensor, comprising:

an optical source configured to emit a beam directed to an opposing surface having a spatially variable reflectance pattern; and

an optical detector situated in relation to the optical source to detect a portion of the beam reflected by the opposing surface and to produce an output signal that varies based on (i) a relative displacement between the reflectance pattern and the optical detector and (ii) a spatially variable reflectance resulting from the relative displacement.

2. The sensor of any preceding claim or claim 1, wherein the optical detector comprises a single detection element and the output signal provides multi-axis displacement information along perpendicular shear axes.

3. The sensor of any preceding claim or claim 1, further comprising an intermediate transparent layer situated adjacent to the optical source and optical detector, wherein the layer is configured to deform to provide the displacement through a mechanical coupling with the opposing surface.

4. The sensor of any preceding claim or claim 3, wherein the intermediate transparent layer is situated to receive and transmit the beam and the reflected portion through the intermediate transparent layer.

5. The sensor of any preceding claim or claim 3, wherein the intermediate transparent layer comprises an elastomer transducer layer.

6. The sensor of any preceding claim or claim 5, wherein the elastomer transducer layer comprises polydimethylsiloxane (PDMS).

7. The sensor of any preceding claim or claim 5, wherein the elastomer transducer layer comprises a thickness and curing characteristics configured to define a shear modulus.

8. The sensor of any preceding claim or claim 3, further comprising a sensor housing configured to support the optical source, optical detector, and/or intermediate transparent layer in fixed relation to each other.

9. The sensor of any preceding claim or claim 8, further comprising a base plate attached to the sensor housing, and/or intermediate transparent layer, wherein the base plate comprises the opposing surface.

10. The sensor of any preceding claim or claim 8, wherein the optical detector comprises an aperture mask configured to define the amount of the detected portion by controlling the amount of area of the opposing surface viewed by the optical detector.

11. The sensor of any preceding claim or claim 10, wherein the spatially variable reflectance pattern comprises a repeating reflectance pattern and the aperture mask comprises a repeating aperture mask pattern associated with the repeating reflectance pattern.

12. The sensor of any preceding claim or claim 11, wherein respective repetition periods of the repeating reflectance pattern and repeating reflectance pattern are configured to provide a tolerance for recalibrating the sensor after a slip displacement between the optical detector and the opposing surface.

13. The sensor of any preceding claim or claim 1, wherein the spatially variable reflectance pattern comprises a spatially variable color reflectance pattern configured to reflect light by different amounts according to the spatially variable color.

14. The sensor of any preceding claim or claim 13, wherein the spatially variable color reflectance pattern comprises a first pattern area having a first color profile, a pair of second pattern areas having a common second color profile and situated on opposing sides of the first pattern area along a first shear axis, and a pair of third pattern areas having a common third color profile and situated on opposing sides of the first pattern area along a second shear axis perpendicular to the first shear axis.

15. The sensor of any preceding claim or claim 14, wherein the spatially variable color reflectance pattern further comprises four fourth pattern area having a fourth color profile having a reflectance common with the second and third color profiles, wherein the four fourth pattern areas are situated in a corner relationship to the first pattern area and the second and third opposing pattern areas.

16. The sensor of any preceding claim or claim 15, wherein the optical source comprises a red, green, blue (RGB) light emitting diode (LED).

17. The sensor of any preceding claim or claim 16, wherein the first color profile is a green color configured to reflect the green light of the RGB LED, the second color profile is one of blue or red color configured to reflect the corresponding blue or red light of the RGB LED, and the third color profile is other one of the blue or red color configured to reflect the corresponding blue or red light of the RGB LED.

18. The sensor of any preceding claim or claim 17, wherein the fourth color profile is a magenta color configured to reflect both the blue and the red light of the RGB LED.

19. The sensor of any preceding claim or claim 13, further comprising a processor and memory configured with processor-executable instructions that cause the processor to:

vary the spectral content of the beam produced by the optical source over time, receive the output signal from the optical detector and associate different output signal times with the timing of the variable spectral content, and

determine a reflectance change associated with the relative displacement.

20. The sensor of any preceding claim or claim 19, wherein the memory is configured with processor-executable instructions that cause the processor to measure, based on the reflectance change, a shear stress between (i) the opposing surface and the (ii) optical source and optical detector.

21. The sensor of any preceding claim or claim 1, wherein the spatially variable reflectance pattern comprises a spatially variable gray scale reflectance pattern configured to reflect light by different amounts according to an intensity dependent gray scale spatial variation.

22. The sensor of any preceding claim or claim 21, wherein the optical source comprises a white light source.

23. The sensor of any preceding claim or claim 1, wherein the optical detector comprises a photoresistor and the output signal comprises a variable resistance signal.

24. The sensor of any preceding claim or claim 1, wherein the optical detector comprises a phototransistor and the output signal comprises a variable voltage or current signal.

25. The sensor of any preceding claim or claim 1, wherein the optical detector comprises a photodiode and the output signal comprises a variable voltage or current signal.

26. A prosthesis, comprising the sensor of any preceding claim or claim 8.

27. The prosthesis of any preceding claim or claim 26, wherein the opposing surface is arranged on a residual limb.

28. The prosthesis of any preceding claim or claim 27, wherein the prosthesis comprises a prosthetic socket and the sensor housing is embedded within the socket.

29. A method, comprising:

emitting a beam from an optical source and directing the beam to an opposing surface having a spatially variable reflectance pattern; and

with an optical detector situated in relation to the optical source, detecting a portion of the beam reflected by the opposing surface and producing an output signal that varies based on (i) a relative displacement between the reflectance pattern and the optical detector and (ii) a spatially variable reflectance resulting from the relative displacement.

SHEAR STRESS SENSOR

ABSTRACT OF THE DISCLOSURE

Sensors include an optical source configured to emit a beam directed to an opposing surface having a spatially variable reflectance pattern, and an optical detector situated in relation to the optical source to detect a portion of the beam reflected by the opposing surface and to produce an output signal that varies based on (i) a relative displacement between the reflectance pattern and the optical detector and (ii) a spatially variable reflectance resulting from the relative displacement. Methods of operation and fabrication of shears sensors are also disclosed.

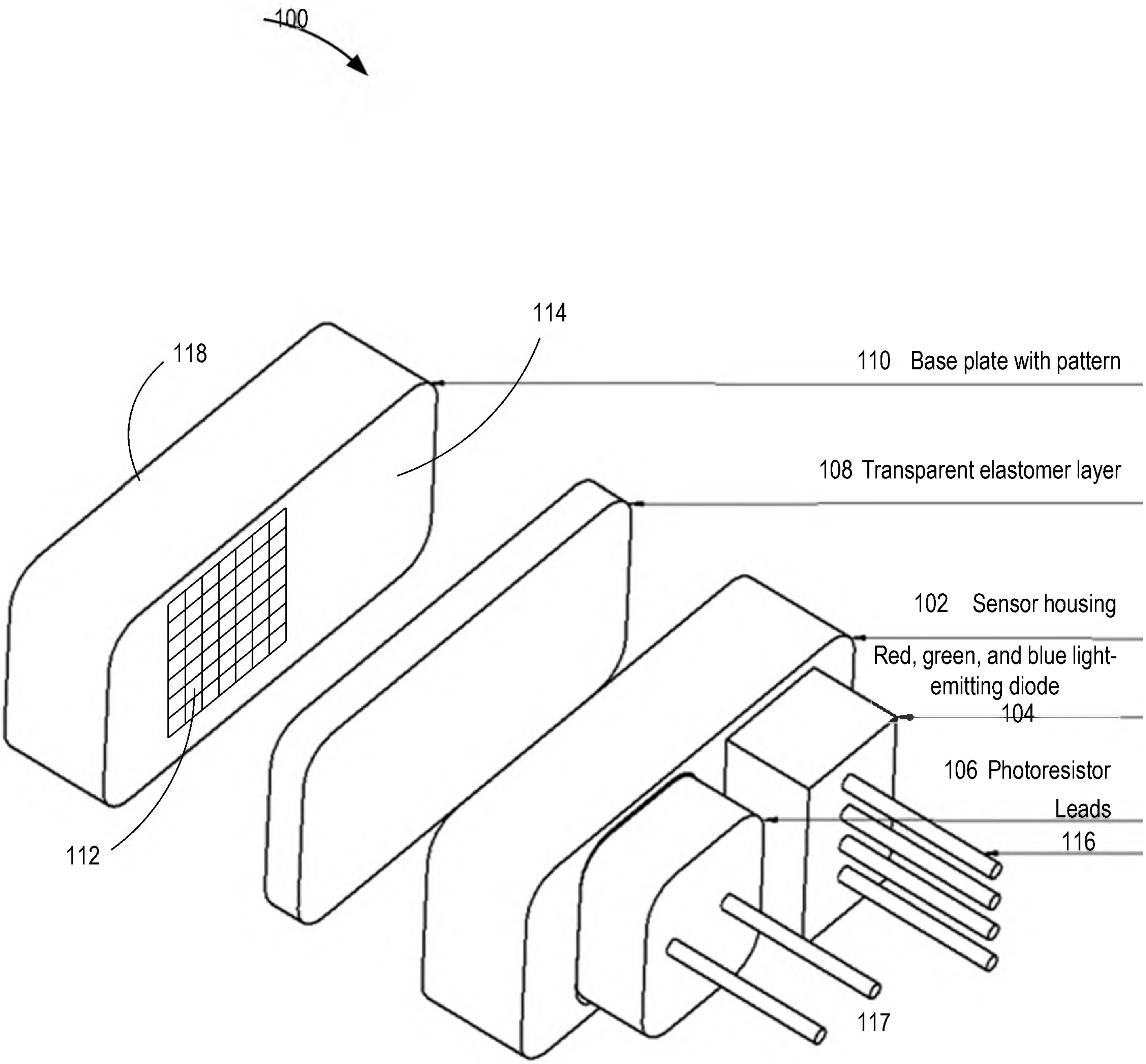

100
114
118
110 Base plate with pattern
108 Transparent elastomer layer
102 Sensor housing
Red, green, and blue light-emitting diode
104
106 Photoresistor
Leads
116
112
117

FIG. 1A

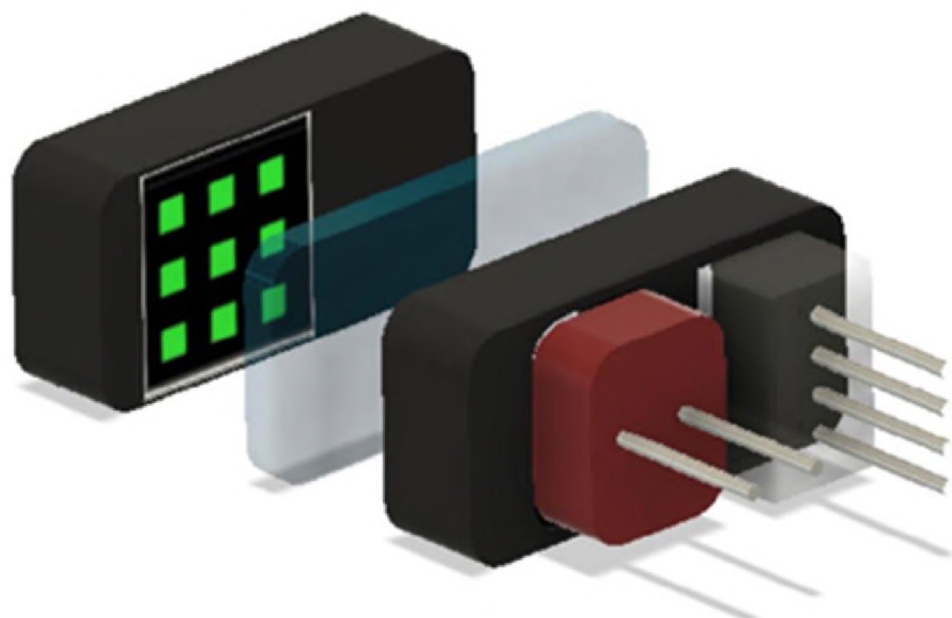


FIG. 1B

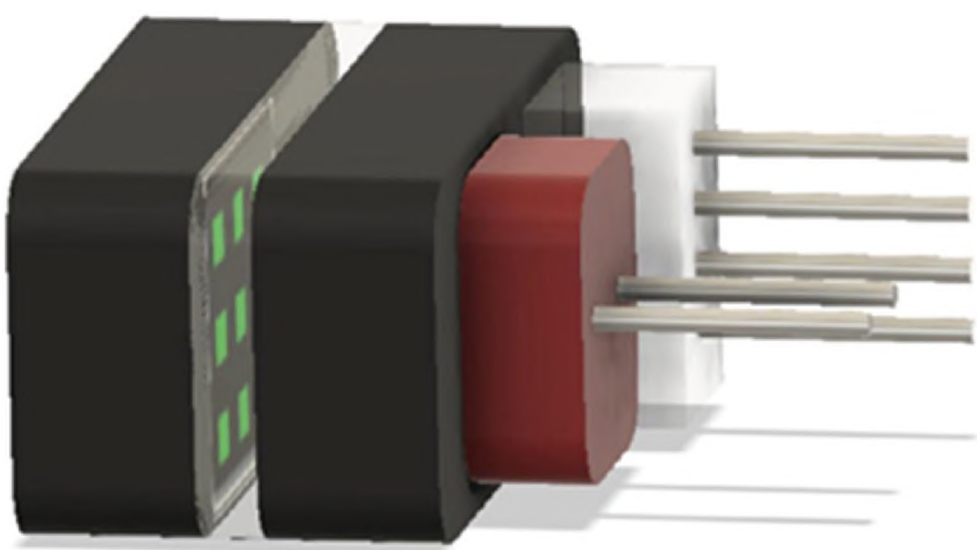


FIG. 1C

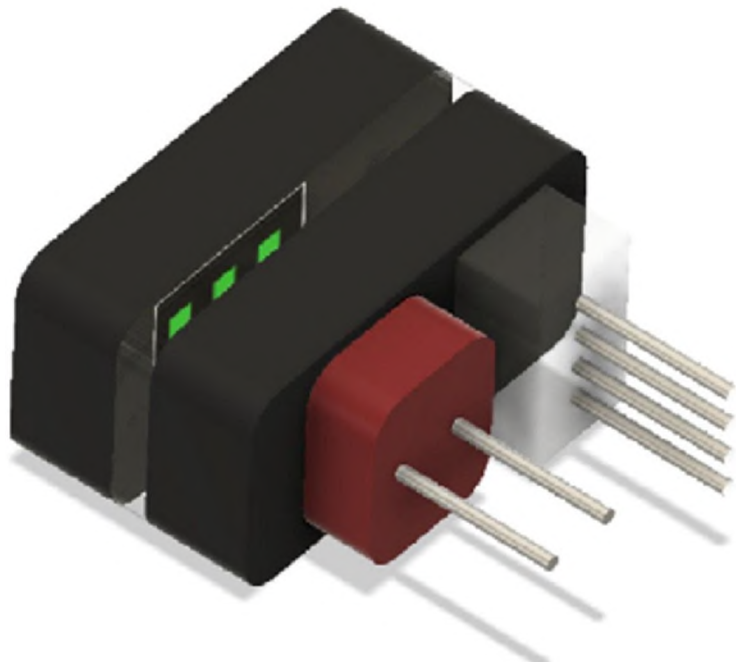


FIG. 1D

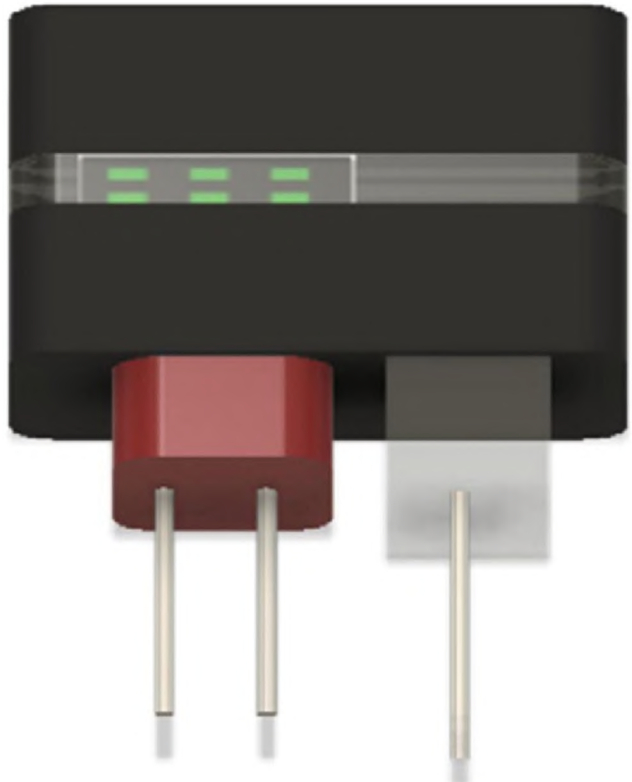


FIG. 1E

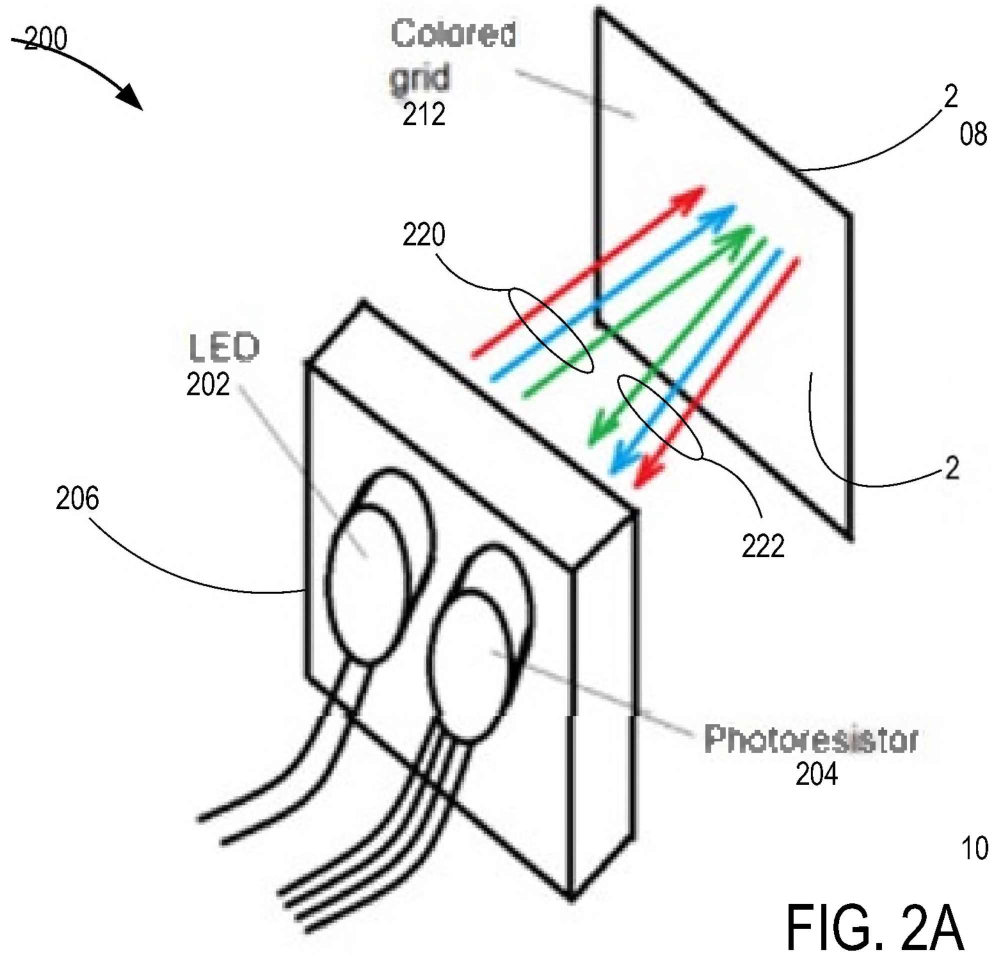
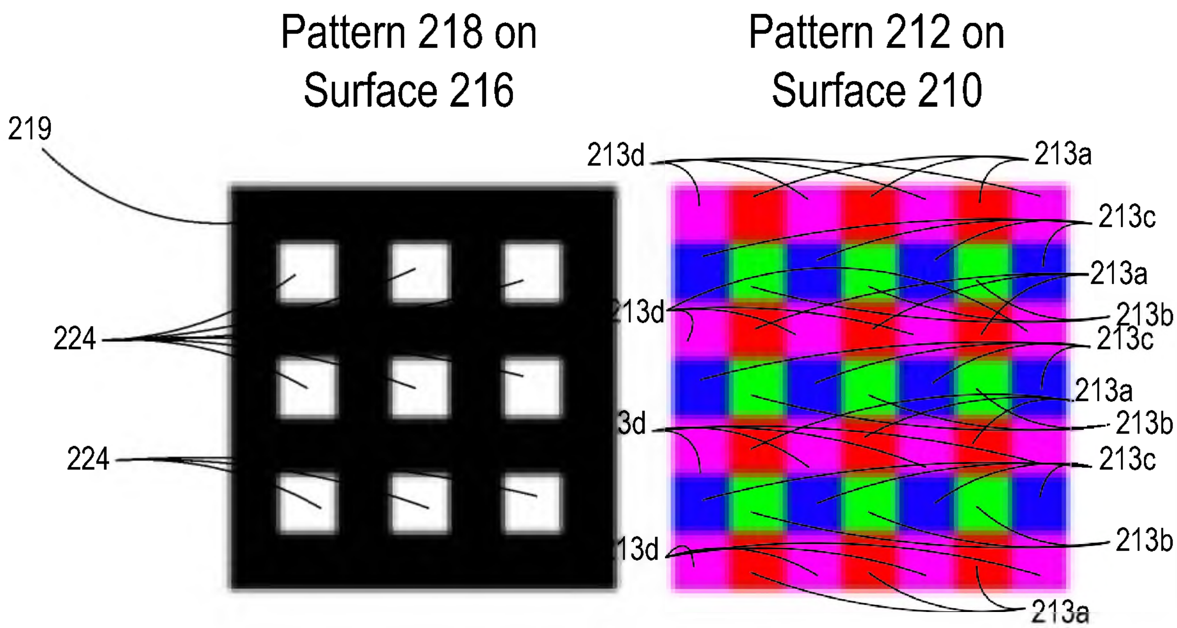

200
Colored grid
212
2
08
220
LED
202
206
2
222
Photoresistor
204
10

FIG. 2A



Pattern 218 on
Surface 216
Pattern 212 on
Surface 210
219
224
224
213d
213a
213c
213a
213d
213b
213c
213a
3d
213b
213c
213b
13d
213a

FIG. 2B

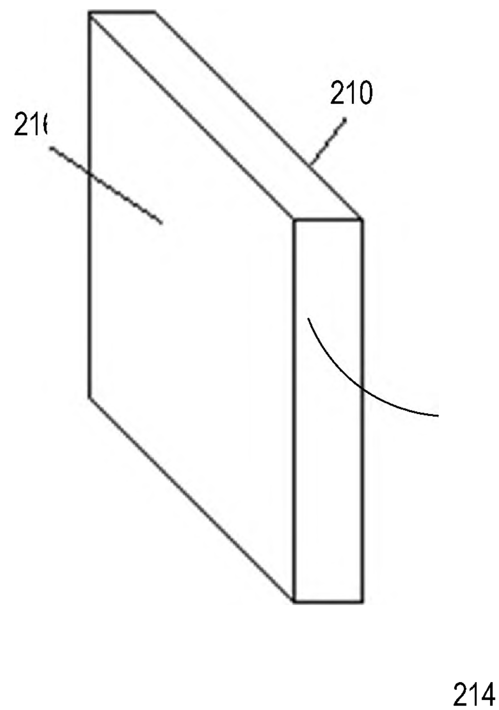


FIG. 2C

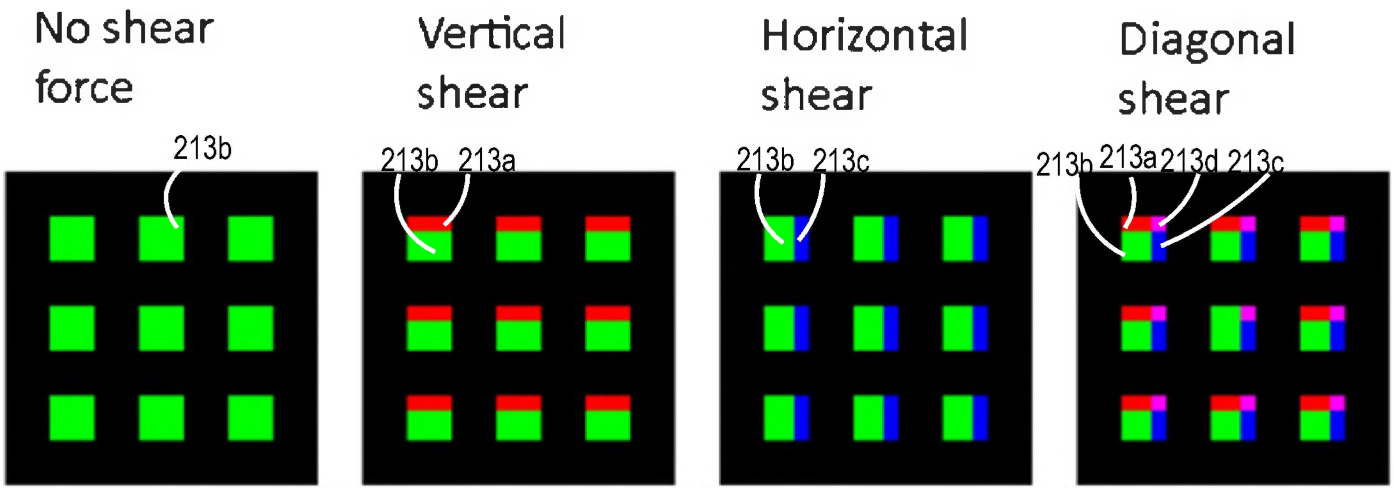

No shear force
Vertical shear
Horizontal shear
Diagonal shear
213b
213b 213a
213b 213c
213b 213a 213d 213c

FIG. 2D

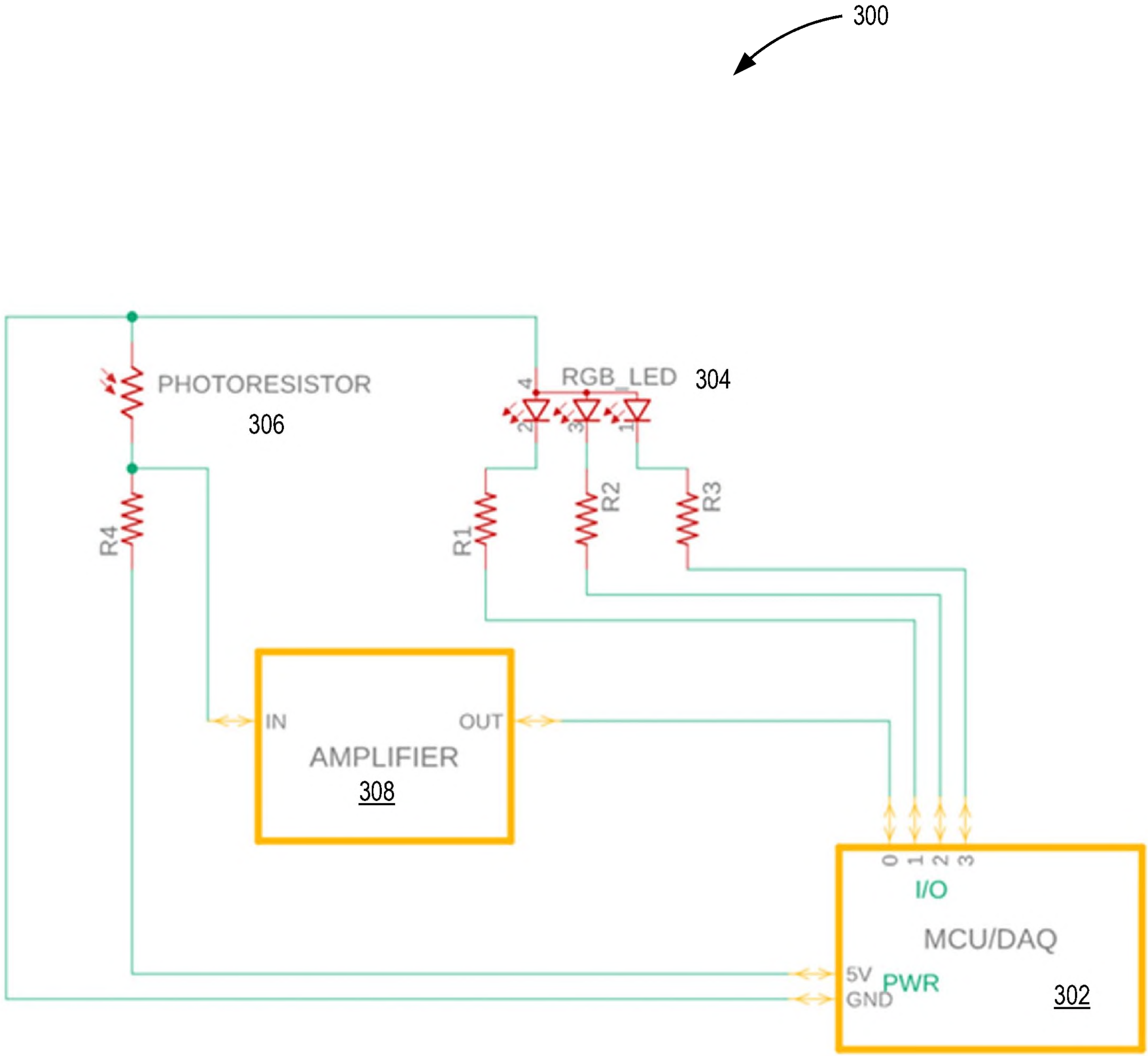

300
PHOTORESISTOR
306
RGB_LED
304
4
2
3
1
R4
R1
R2
R3
IN
OUT
AMPLIFIER
308
0
1
2
3
I/O
MCU/DAQ
5V
PWR
GND
302

FIG. 3

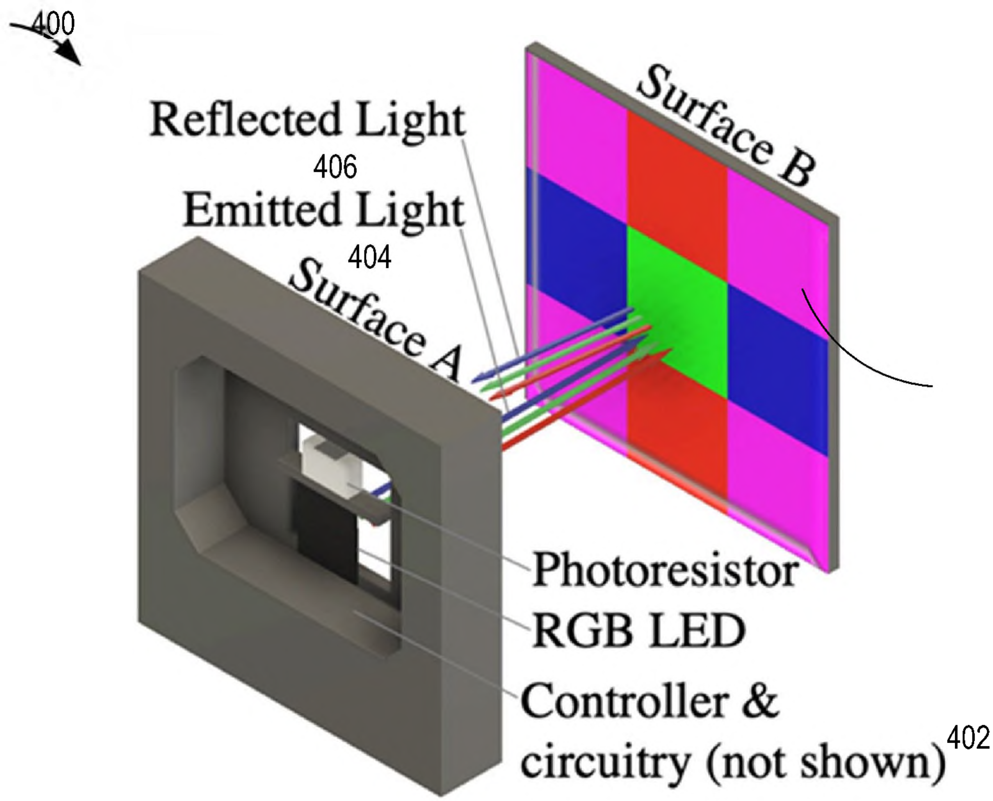

400
Reflected Light
406
Emitted Light
404
Surface A
Surface B
Photoresistor
RGB LED
Controller &
circuitry (not shown)
402

FIG. 4A

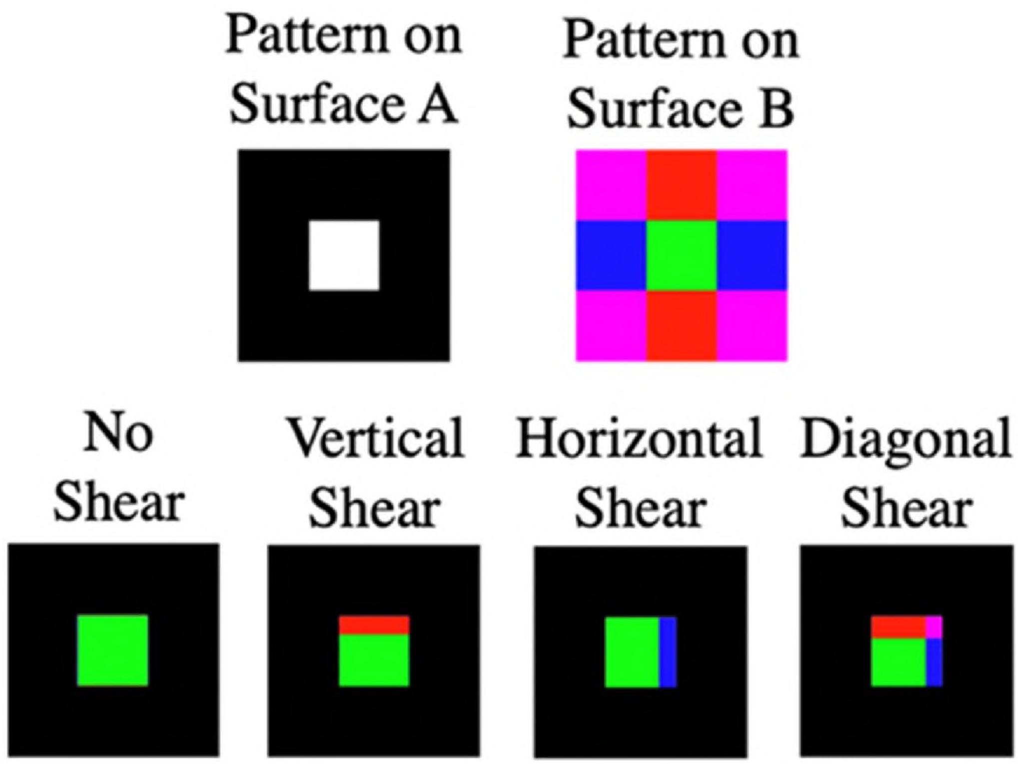

Pattern on Surface A
Pattern on Surface B
No Shear
Vertical Shear
Horizontal Shear
Diagonal Shear

FIG. 4B

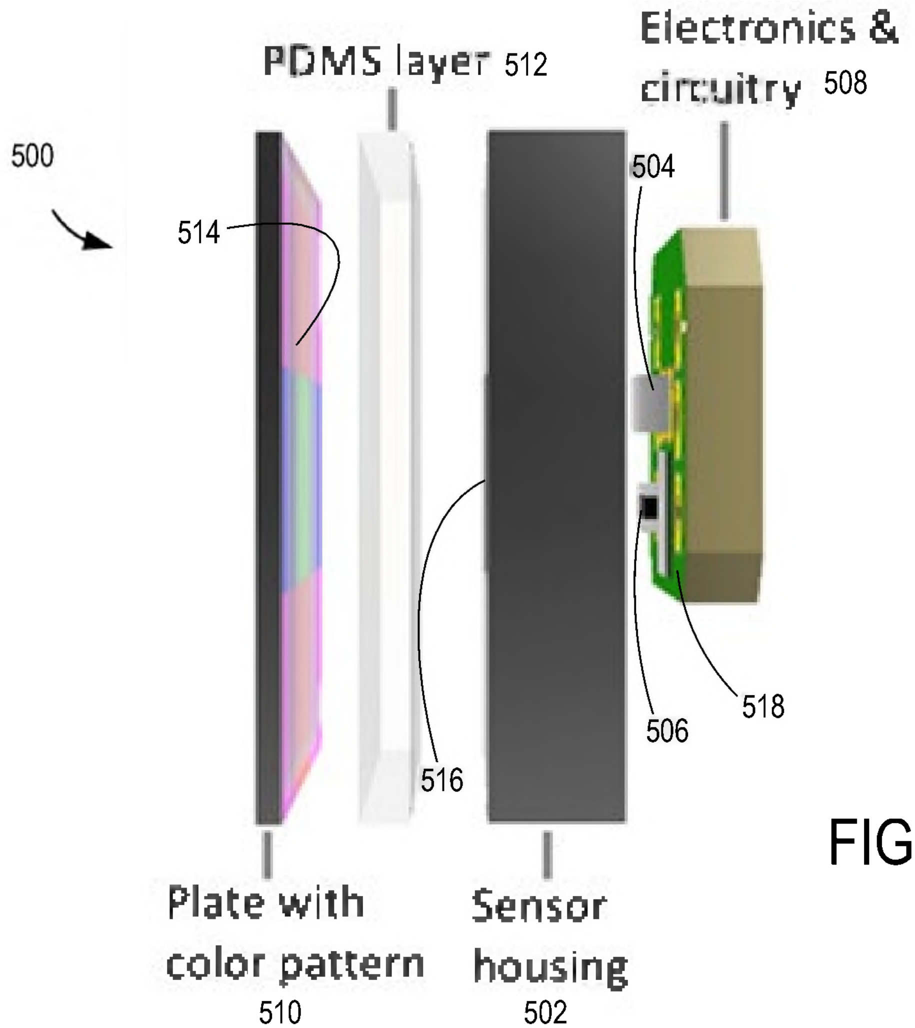
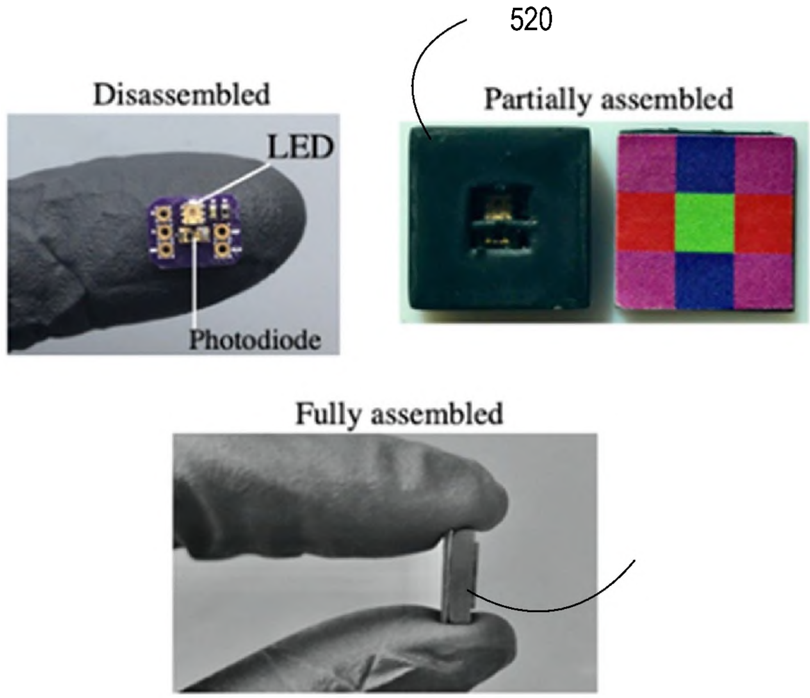
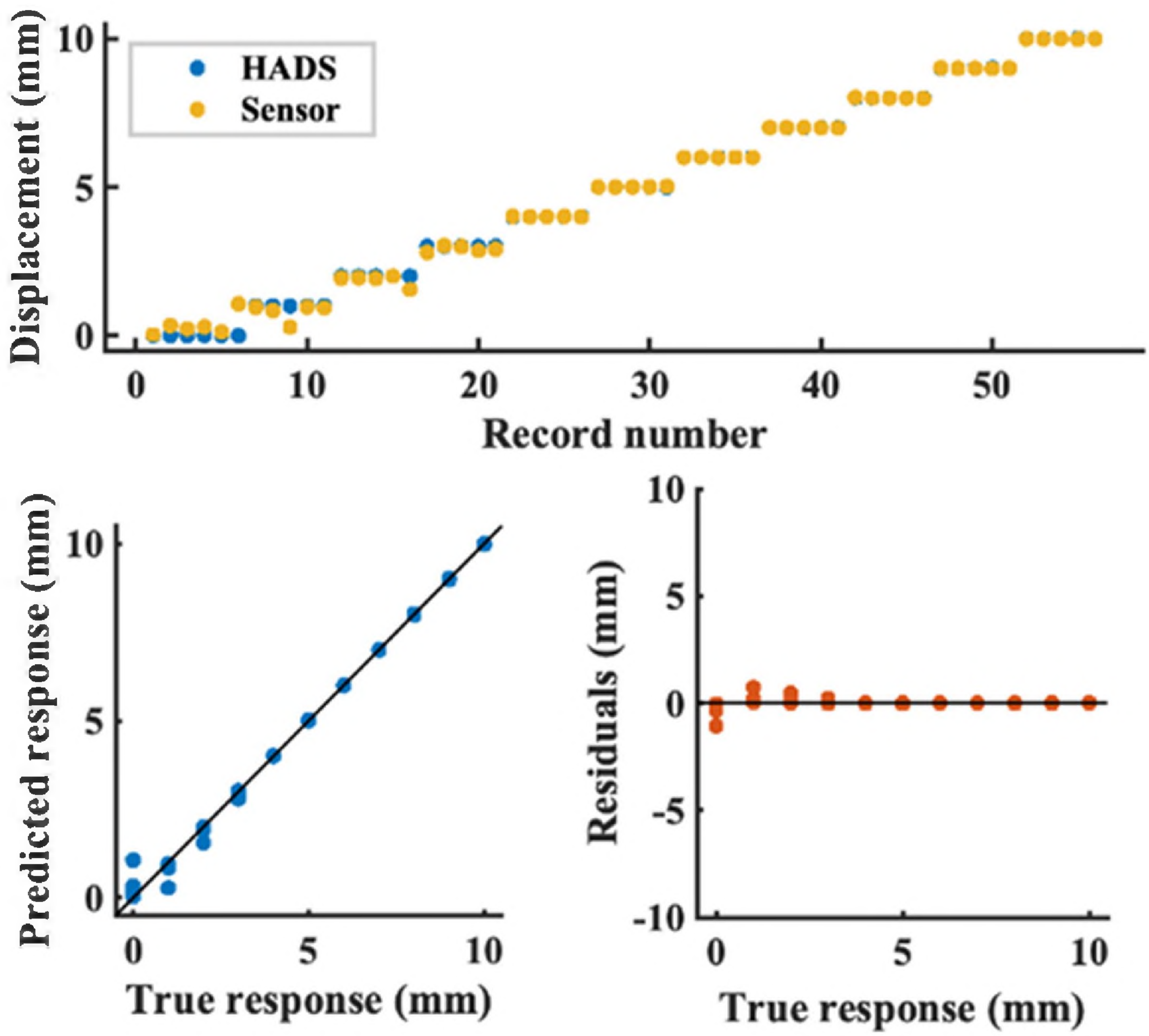

PDMS layer 512
Electronics &
circuitry 508
500
514
504
516
506
518
Plate with
color pattern
510
Sensor
housing
502

FIG. 5A


520
Disassembled
LED
Photodiode
Partially assembled
Fully assembled

520

FIG. 5B



Displacement (mm)
HADS
Sensor
Record number
0
5
10
20
30
40
50
Predicted response (mm)
True response (mm)
Residuals (mm)
-5
-10
True response (mm)

FIG. 6A

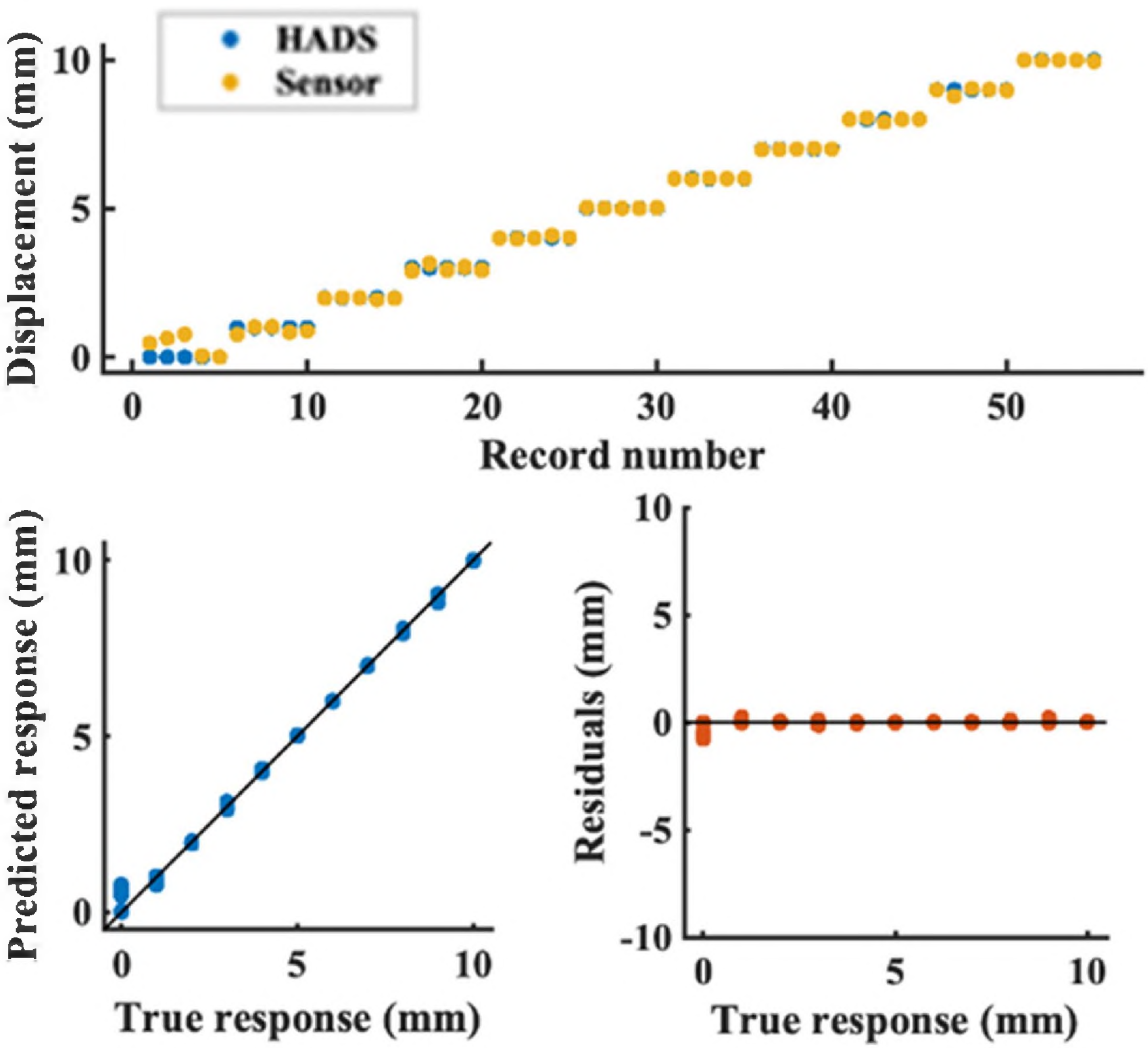
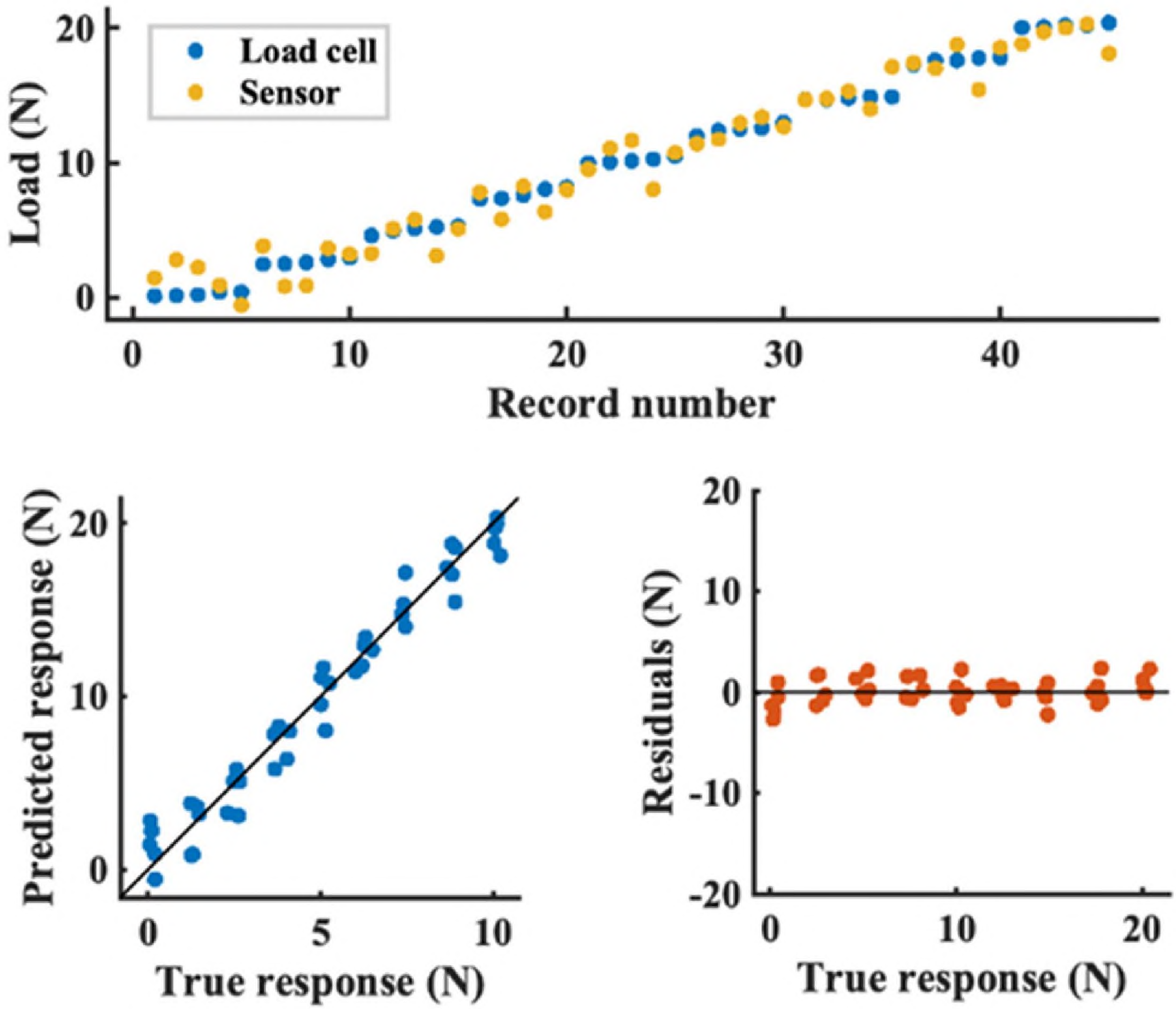
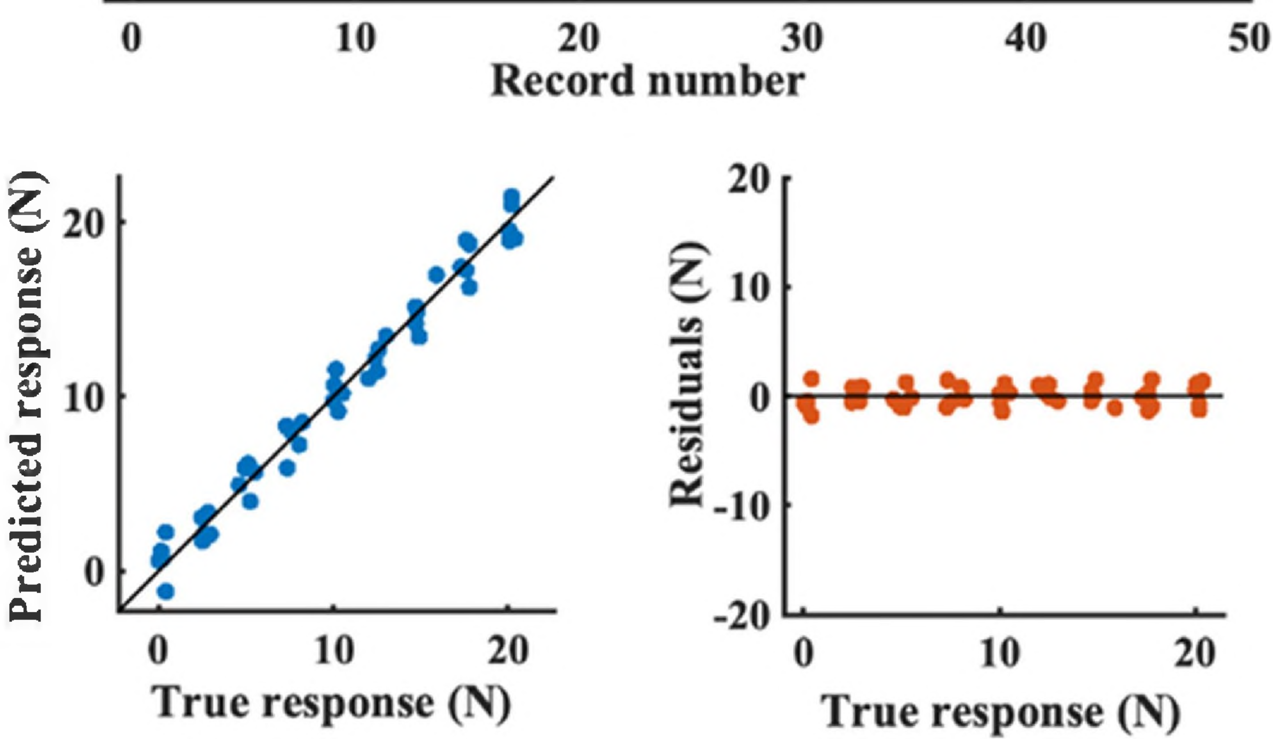

HADS
Sensor
Displacement (mm)
10
5
0
0
10
20
30
40
50
Record number
Predicted response (mm)
10
5
0
0
5
10
True response (mm)
Residuals (mm)
10
5
0
-5
-10
0
5
10
True response (mm)

FIG. 6B



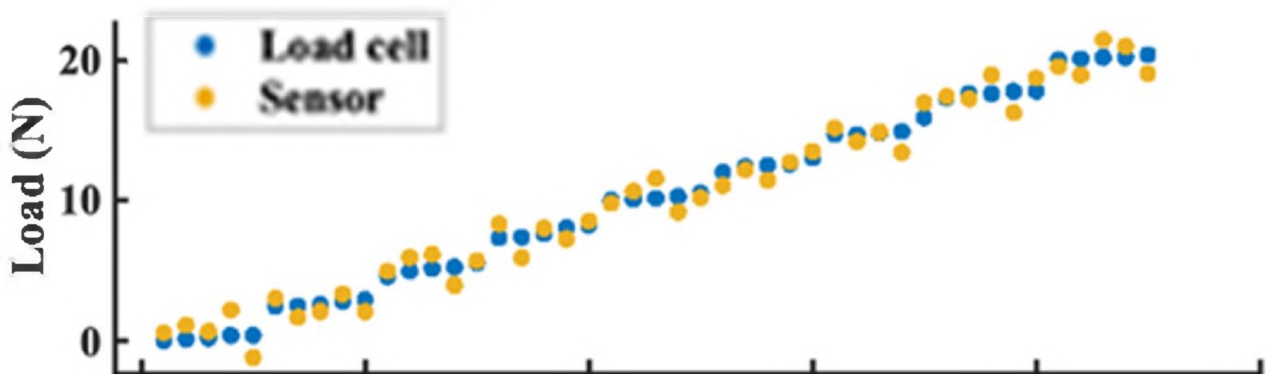
Load cell
Sensor
Load (N)
Record number
Predicted response (N)
True response (N)
Residuals (N)
True response (N)

FIG. 7A

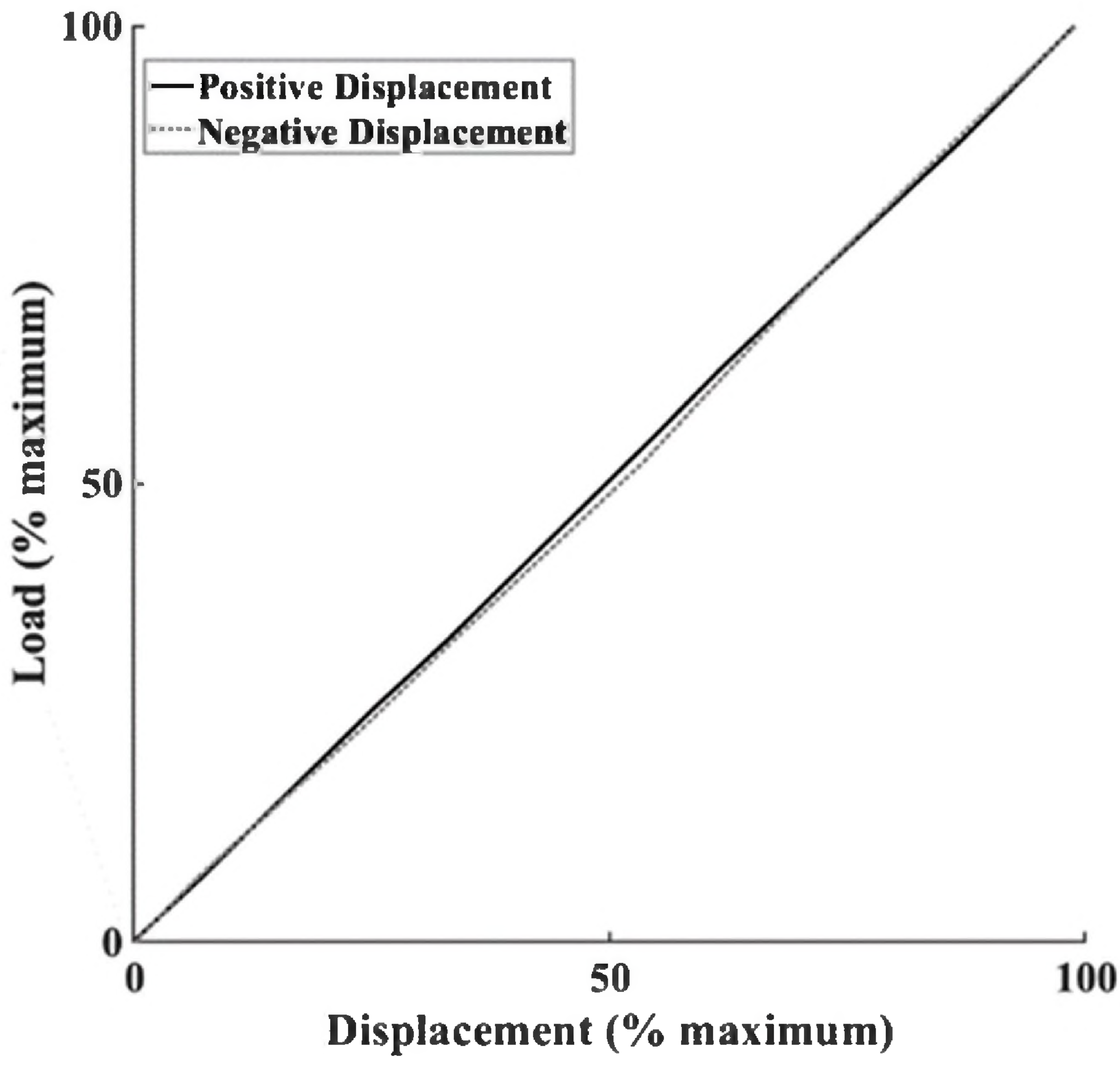


0
10
20
30
40
50
Record number
Predicted response (N)
20
10
0
0
10
20
True response (N)
Residuals (N)
20
10
0
-10
-20
0
10
20
True response (N)

FIG. 7B



Load (N)
0
10
20
Load cell
Sensor



Positive Displacement
Negative Displacement
Load (% maximum)
Displacement (% maximum)
0
50
100
0
50
100

FIG. 8

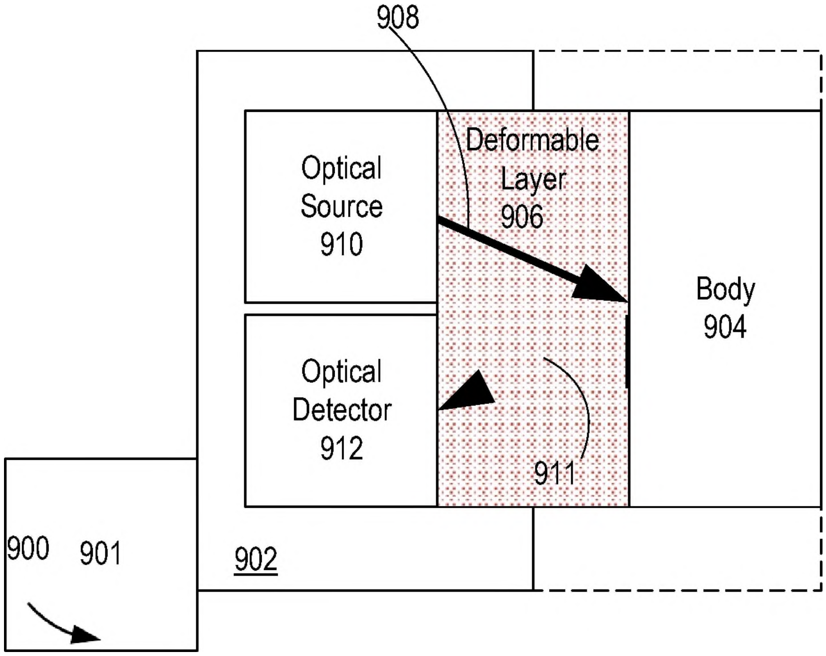

908
Optical
Source
910
Deformable
Layer
906
Body
904
Optical
Detector
912
911
900
901
902

FIG. 9A

FIG. 9B

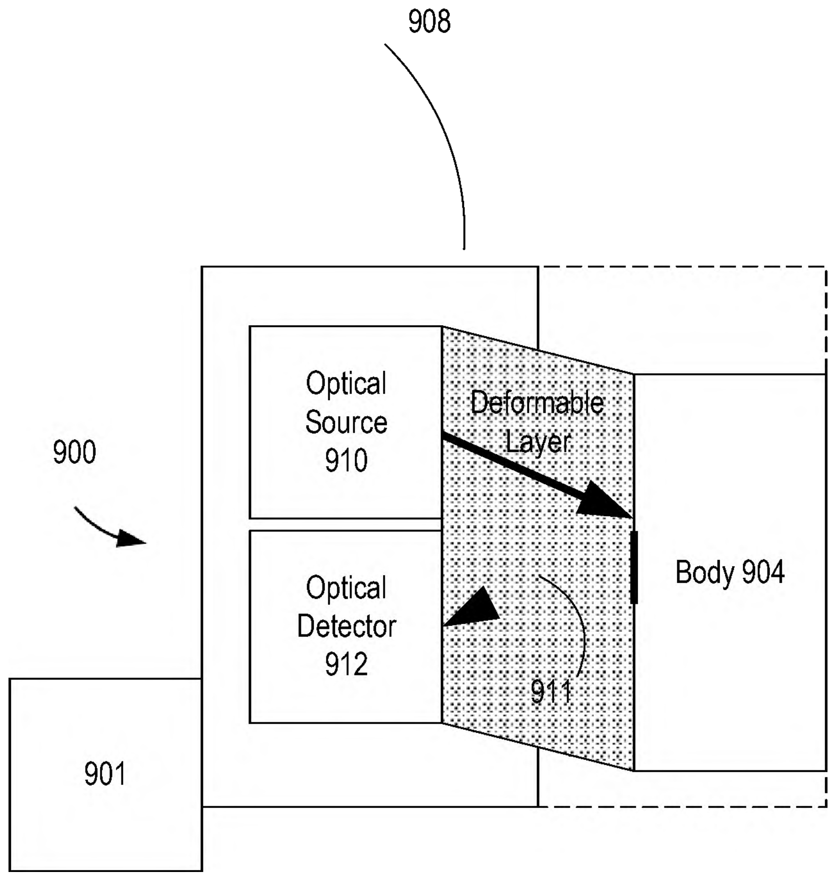

908
900
Optical
Source
910
Optical
Detector
912
Deformable
Layer
911
Body 904
901

FIG. 9B

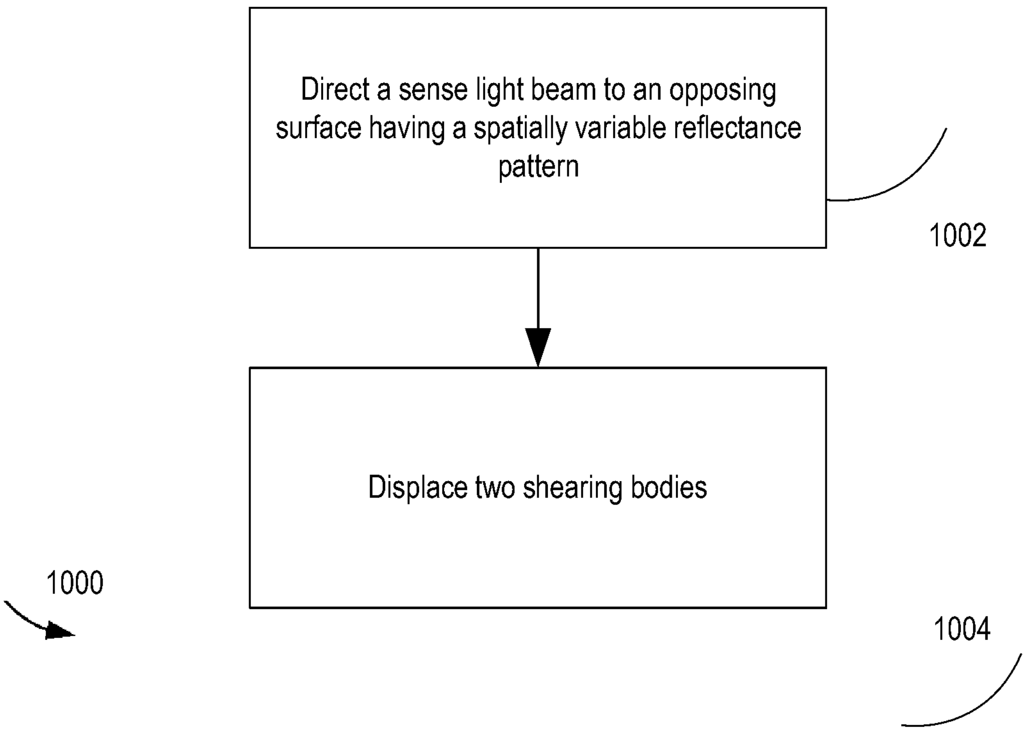

Direct a sense light beam to an opposing surface having a spatially variable reflectance pattern
1002
Displace two shearing bodies
1000
1004

FIG. 10

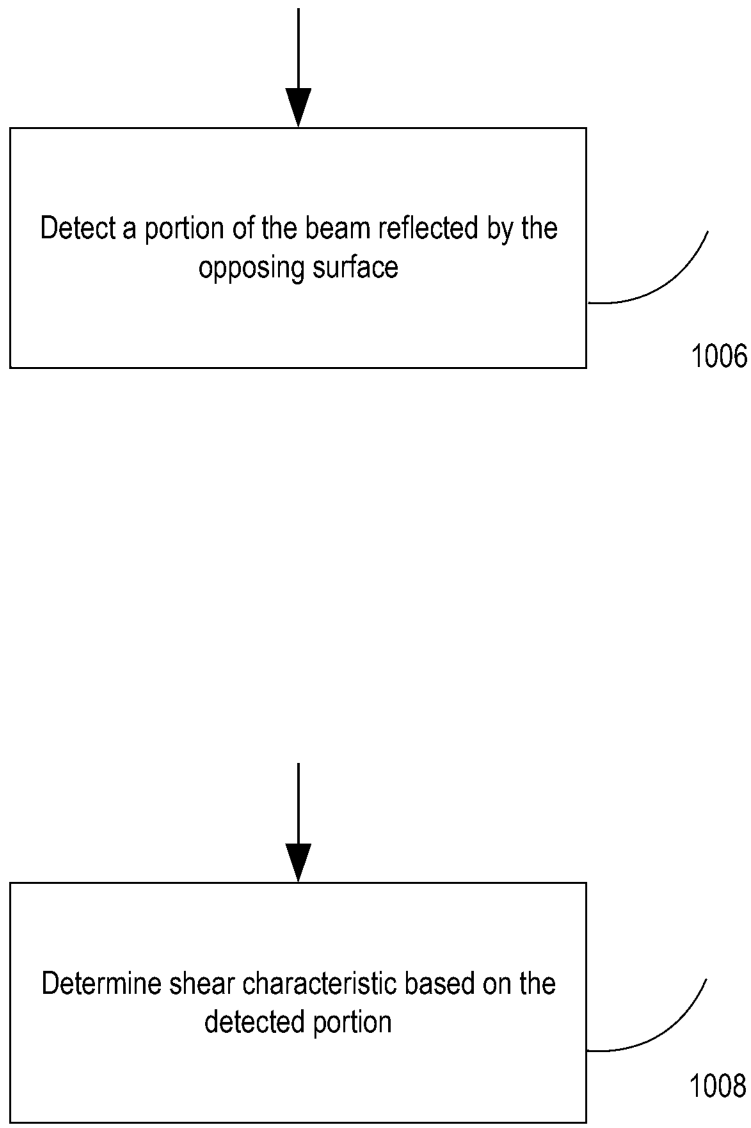

Detect a portion of the beam reflected by the opposing surface
1006
Determine shear characteristic based on the detected portion
1008

FIG. 10

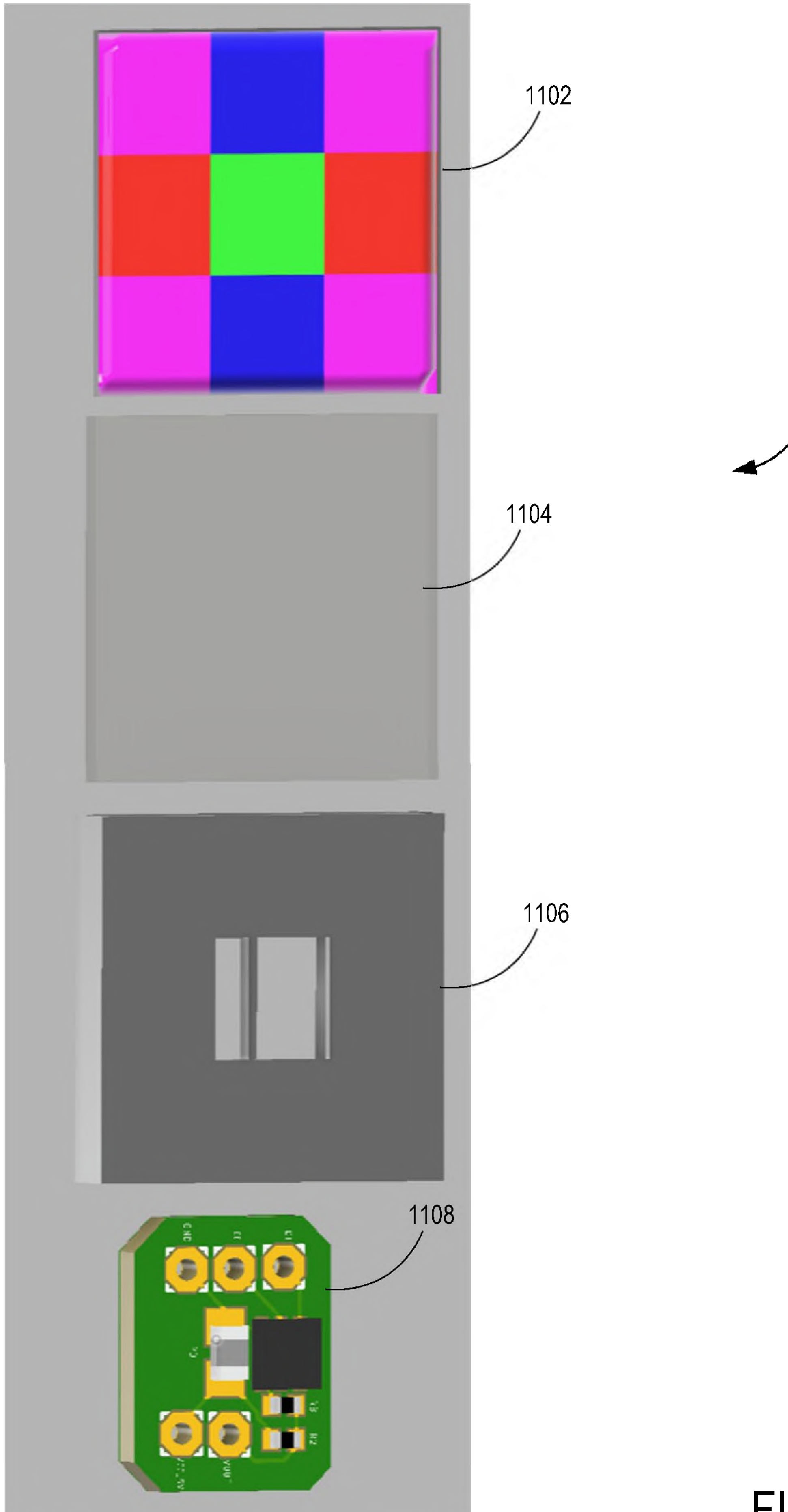


FIG. 11A

1100

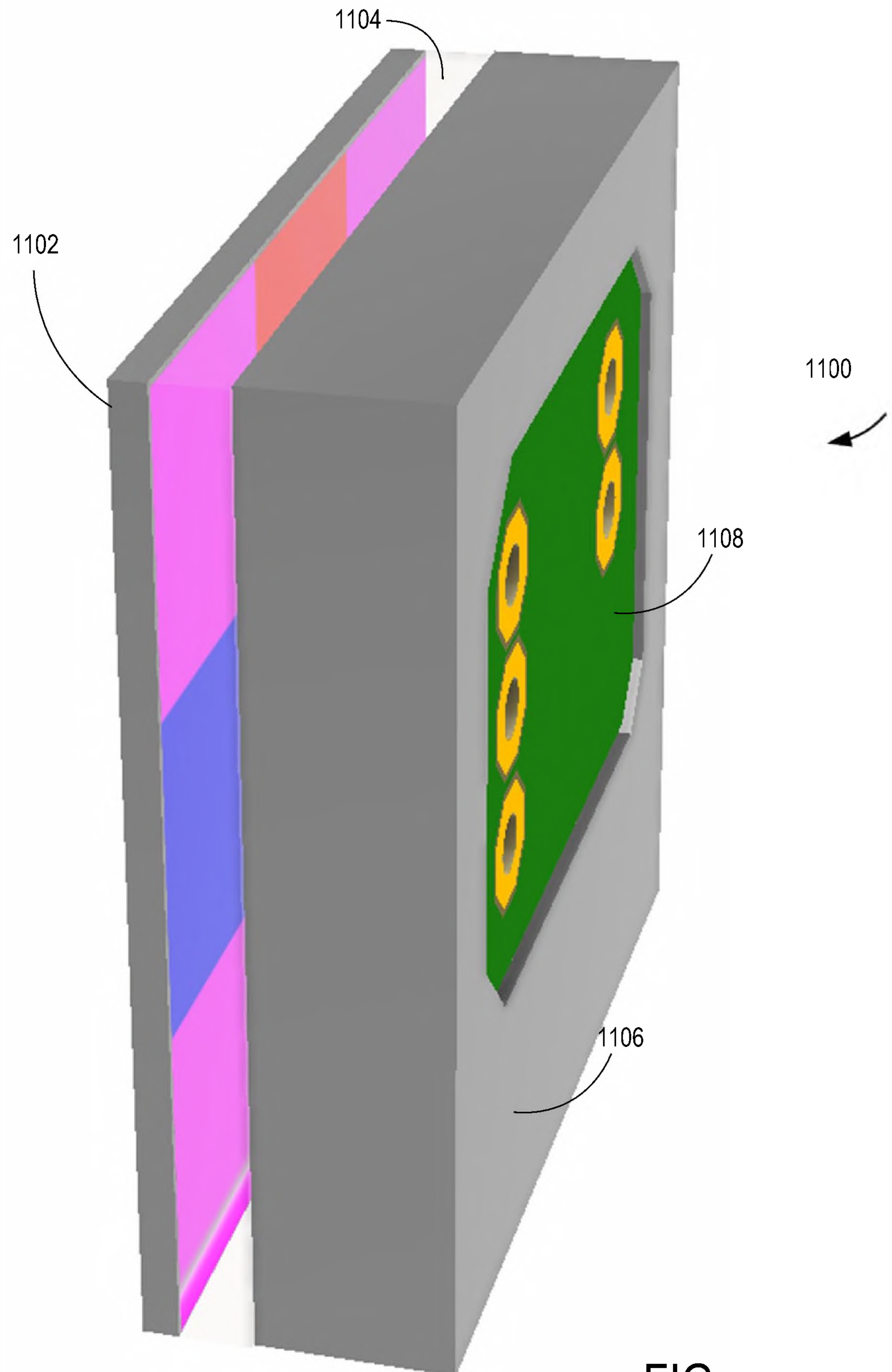


FIG. 11B

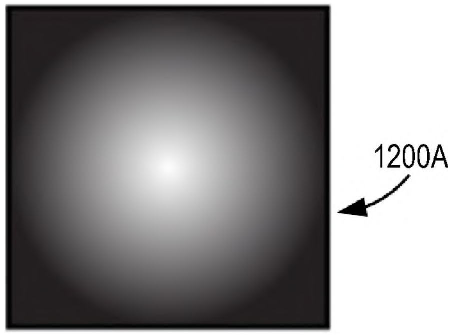


FIG. 12A

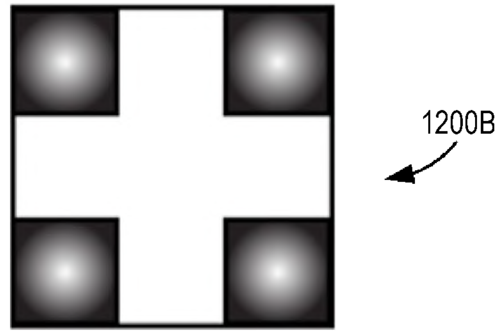


FIG. 12B

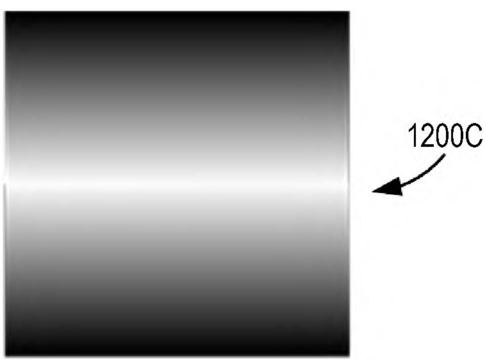


FIG. 12C

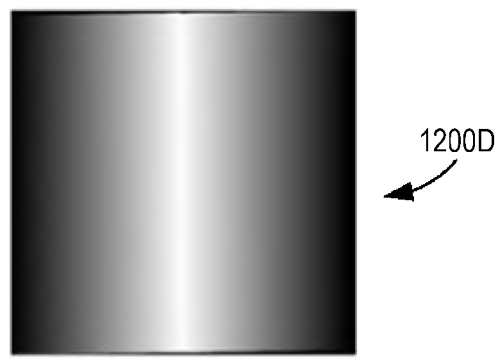


FIG. 12D

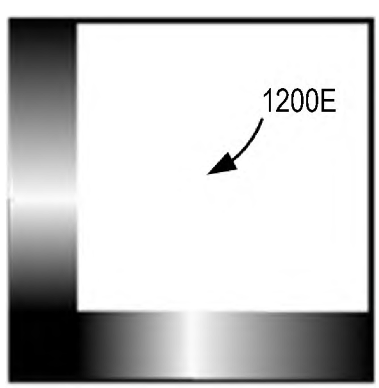


FIG. 12E

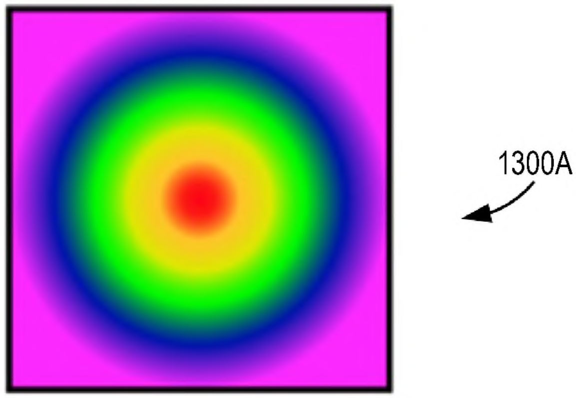


FIG. 13A

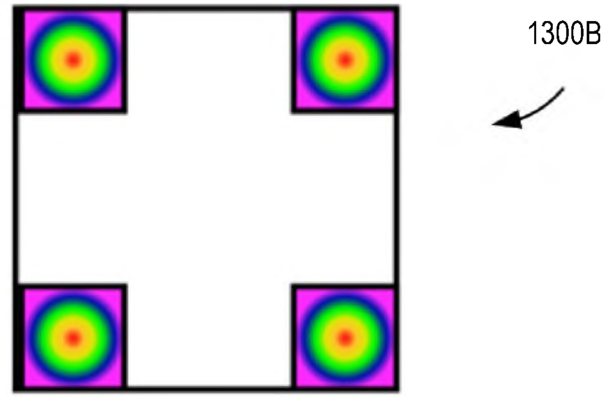


FIG. 13B

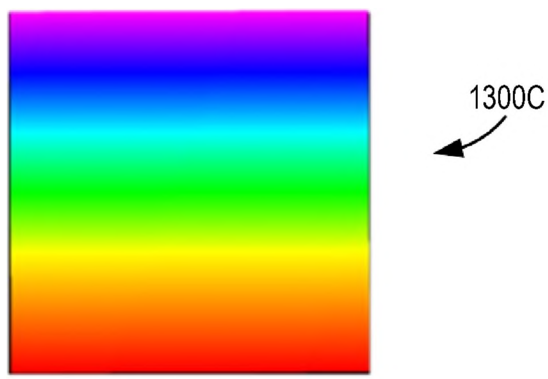


FIG. 13C

FIG. 13D

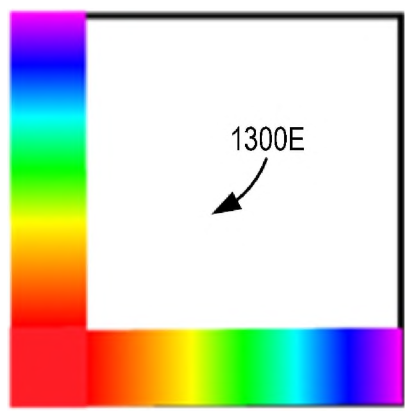


FIG. 13E

1300D

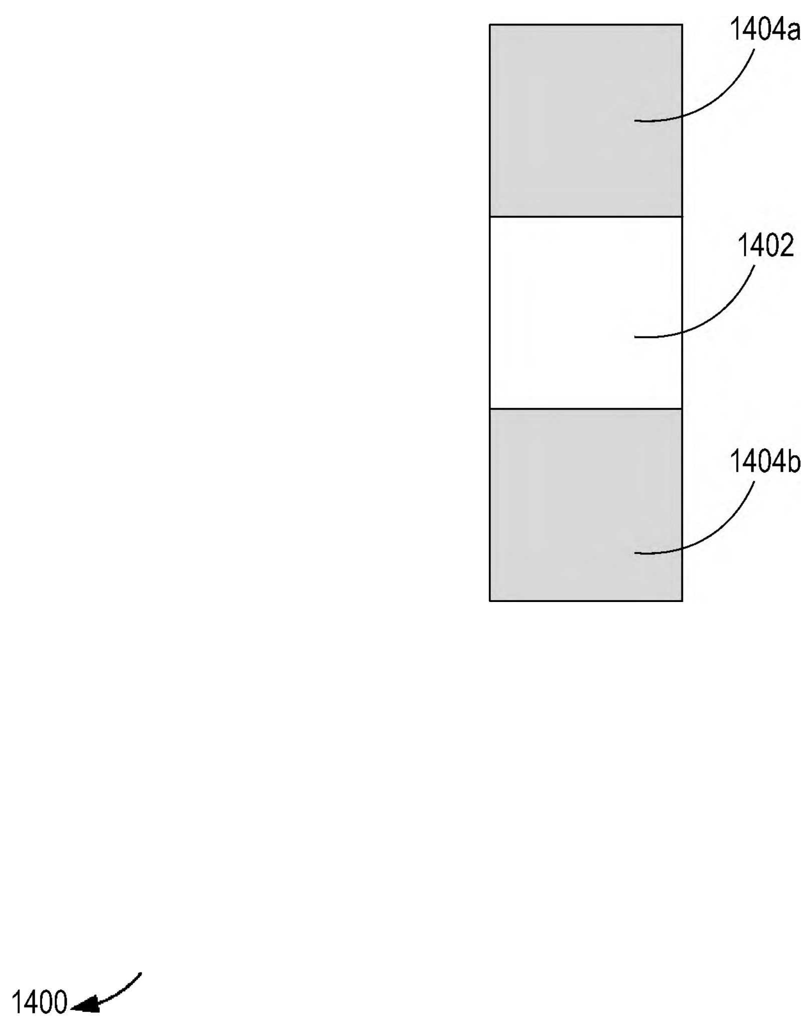


FIG. 14