SWELL

the prosthetic surf foot

Zachary Samalonis • Yuhan Zhang

THE SWELL SURF FOOT

Created by Zachary Samalonis
and Yuhan Zhang

THANKS IN PART TO:
Eileen Martinson, Thomas Jefferson Industrial Design Department, The Class of 2020, Ygor Carvalho, Lance Vargas, Dana Cummings, and Jean Paul Veaudry.

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Class of 2020
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Did you enjoy this book? We love to hear from our readers and fellow designers. Please email us at *zachsamdesigns@gmail.com.*

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Whether it is your first time in the ocean or you have been surfing for a lifetime this is for you...

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Swell

a low-cost waterproof prosthetic foot with increased ankle mobility to enable correct surfing mechanics.


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WHO ARE SURFERS

“There’s something special about surfing and I love it all. The history, the brotherhood and mostly the people. I couldn’t imagine my life without surfing in it, it’s been too helpful in dealing with my amputation. **It’s my therapy**.”

-Brian Bott, Californian Amputee Surfer and Photographer

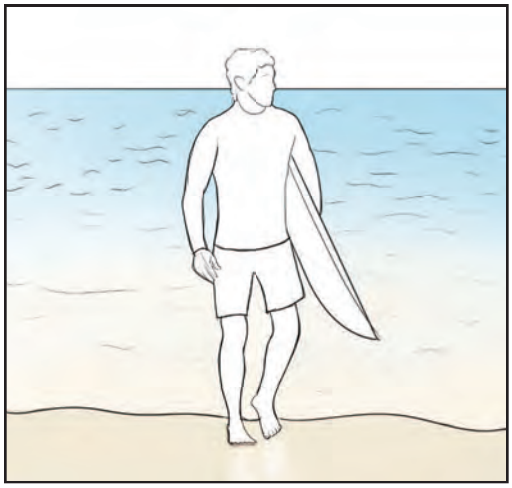
SURFING IS A CULTURE

Surfing is an international sport, first popularized in the United States in the 1960s. Surfing is a lifestyle, one that must be experienced to truly be understood. It is about becoming one with the ocean and feeling the waves.

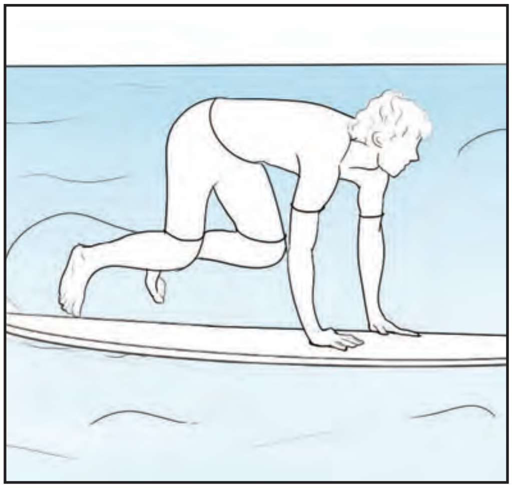
For many individuals, especially those who have PTSD or other medical conditions, surfing has given them opportunities to heal. Many amputees feel the same way.

THE BASICS
OF SURFING

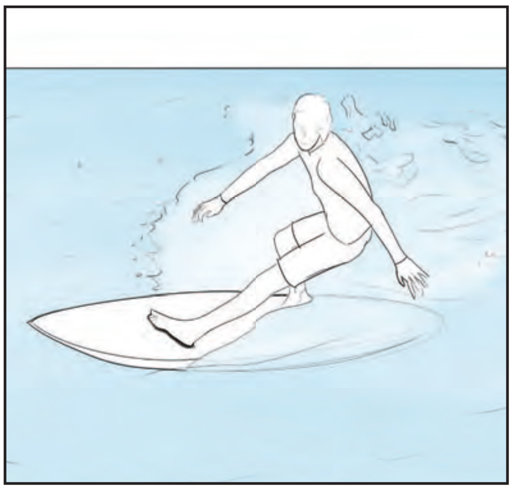
Surfing can be broken down into three stages. Each of these stages has their own unique challenges that we had to consider when creating our prosthetic foot. In order to better understand what physically went into each of these stages, we observed videos of surfers and then recreated these motions on dry land.



GETTING TO THE OCEAN



THE POP-UP



RIDING THE WAVE

GETTING INTO THE OCEAN

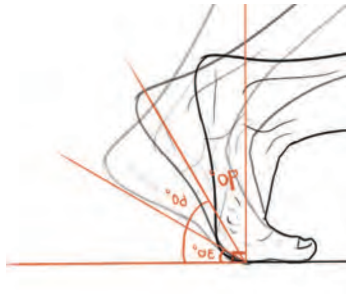
The human ankle can move various degrees in several directions. In order to create a prosthetic someone could surf with, we had to first consider how they would get to the ocean. Walking contains two dominant motions in the ankle, dorsiflexion and plantar flexion.

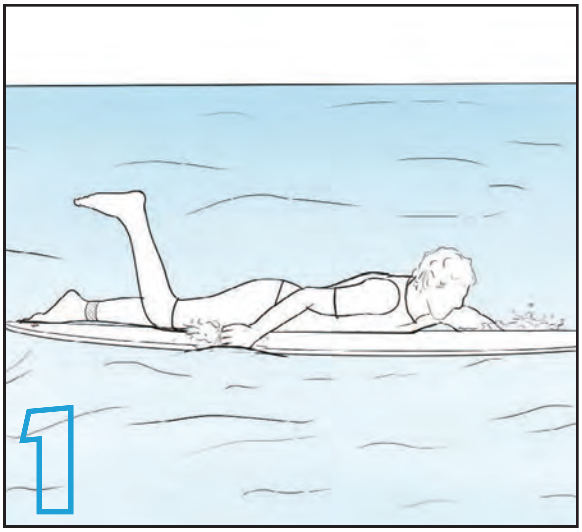
DORSIFLEXION

PLANTAR FLEXION

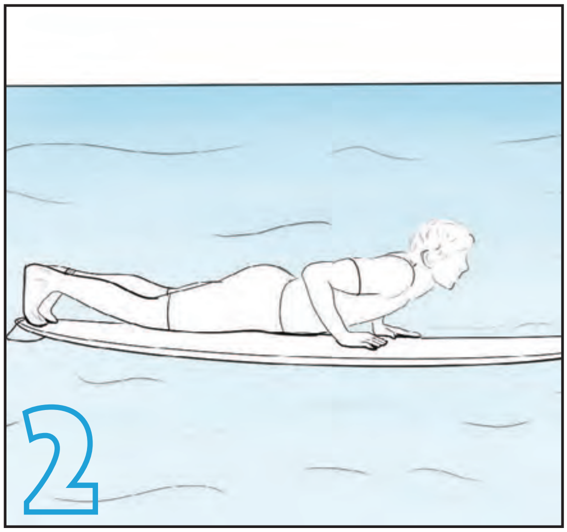
THE POP-UP

The act of popping up is how surfers mount the board and surf the wave. For beginners this is one of the hardest things to learn. For amputees many times the motion is altered, because the prosthetic doesn't work in their favor. Flexion between 30° and 90° was needed.

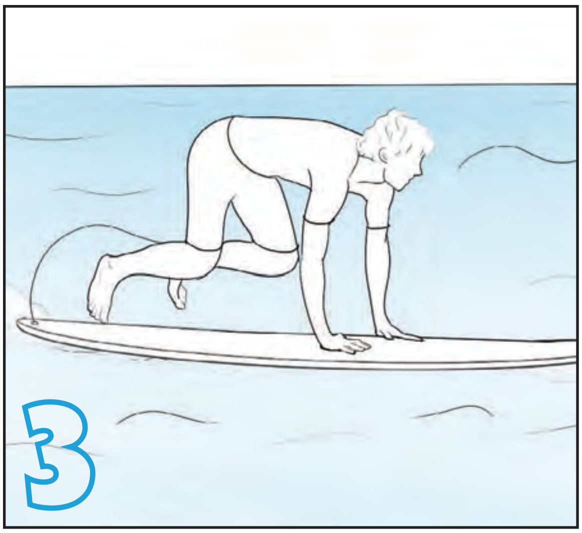




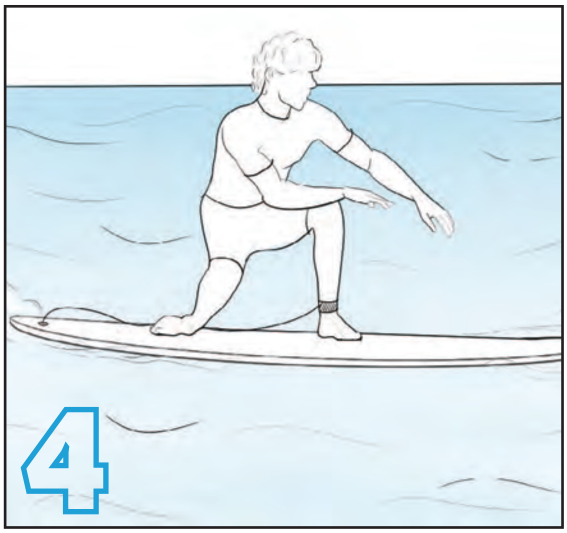
PADDLING OUT



POSITION THE HANDS



SHIFT THE FEET



STAND UP

RIDING THE WAVE

REGULAR

(Left Foot Forward)

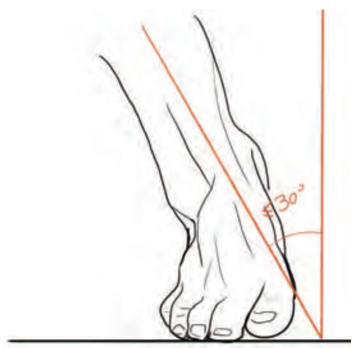
GOOFY

(Right Foot Forward)

INTERIOR AND EXTERIOR FLEX

In order to create a prosthetic that would mimic the human foot we had to observe the two surf positions and determine the minimum angles our foot and "ankle" had to meet.

Interior flex of at least 60˚



Exterior flex of at least 30˚

CONSUMER AND MARKET RESEARCH

"Being in the water is the only time I truly feel limited as an amputee. I can run and bike and walk, but when it comes to the beach it's hard. I always need to plan what I am going to do and how I am going to do it."

- Redmond Ramos, Left BK Amputee Surfer

A NEW WAVE

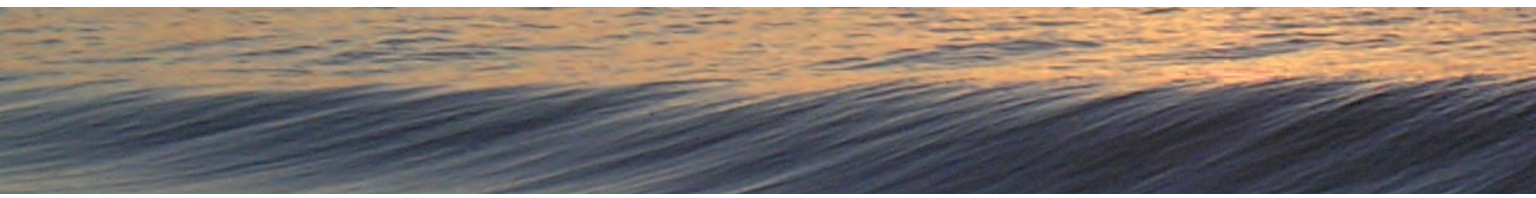
Surfing is one of the newest sports to make it into the 2020 Olympics in Japan. It's also something more and more people with disabilities, both physical and cognitive, are taking part in. More than 30 countries have adaptive surf programs, geared to those with disabilities; the International Surfing Association has petitioned the International Paralympic Committee to add adaptive surfing to the Paris games in 2024.

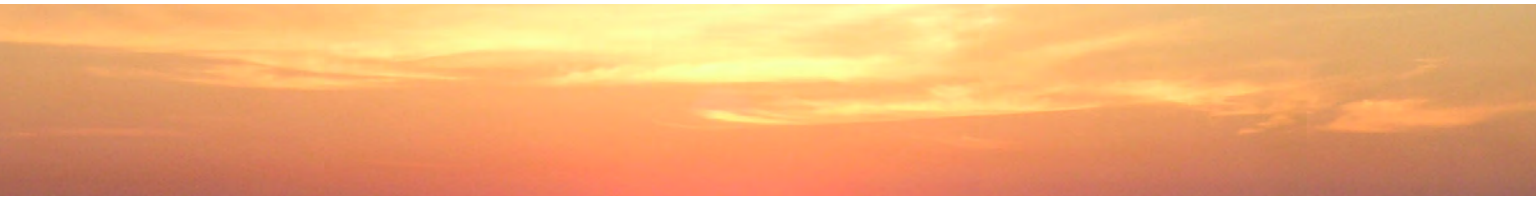
In 2020, more people will be exposed to surfing than ever before.

THE CHALLENGE

Each year there are 185,000 new lower extremity amputations within the United States. Surfing can play a significant role in the lives of people with disabilities by promoting physical well being, combating discrimination, building confidence, and playing an important role in the rehabilitation process. However, the lack of prosthetic devices designed for surfing makes the **sport physically and financially challenging** for people with physical disabilities.

> "We need the industry to make us prosthetics made for surfing and right now we modify them to do that mostly at the expense of losing our warranties."
>
> *- Rodney Roller,*
> *Right BK Amputee Surfer*





MEETING LANCE

From the start we knew we would need an amputee to work with. When searching we discovered Lance Vargas, a **NJ surfer** who was injured a few years ago and needed to have is left leg amputated below the knee. Since Lance had **experience surfing before** his amputation he knew what he was missing and could inform us on what our device needed.

OUR TEAM OF SURFERS

After talking to Lance we learned we needed to talk to individuals who had experience surfing as an amputee. By talking to various adaptive surfers globally, we were able to see what equipment they used and where it failed.

Rodney Roller

Amputation: Right Below the Knee (BK)

From California, Rodney is a 2 time World Adaptive Surf Champion and a Sponsor for RushFoot.

Dana Cummings

Amputation: Left Below the Knee (BK)

From California, Dana is a US military veteran and the CEO of AmpSurf, an organization dedicated to helping those with disabilities surf.

Jean-Paul Veaudry

Amputation: Right Below the Knee (BK)

From South Africa, Jean-Paul has won several adaptive surf championships.

Redmond Ramos

Amputation: Left Below the Knee (BK)

A US military veteran from California, Redmond is a casual surfer and has been featured on several TV shows such as *The Amazing Race.*

Ty Tucket

Amputation: Left Above the Knee (AK)

Originally from Philadelphia, now living in California, Ty has been surfing for several years.

Ryan Johnson

Amputation: Left Below the Knee (BK)

From West Virginia, Ryan was a surfer before his accident and wanted to continue to shred waves after his amputation.

Fabrizio Passetti

Amputation: Right Below the Knee (BK)

From Italy, Fabrizio is a champion surfer who has competed in competitions worldwide.

DISCOVERING KEY INSIGHTS

Each of the surfers showed us different problems; many of them experienced similar issues. These anecdotal stories allowed us to develop key insights.

STIFF PROSTHETICS

Redmond surfs with a prosthetic that has the ability to lock at various angles. While this is good for one position, the inability to change it makes walking and other positions difficult.

SLIPPING WHILE POPPING UP

Many amputees have to alter their pop-up to accommodate their prosthetic. Dana's foot lacks the proper grip and flexibility to produce these movements.

ANKLE MOBILITY

Like almost everyone we talked to, the lack of mobility in the ankle hurts Jean-Paul's balance when surfing. While he has adapted, there is quite the learning curve to it.

ACCESSIBILITY

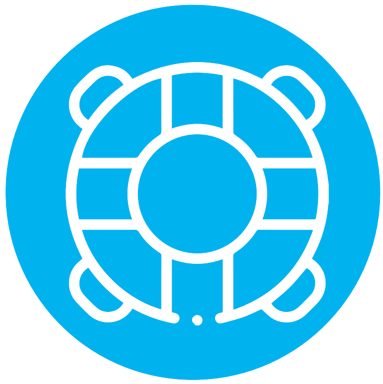
Rodney has been pushing for access to affordable equipment for over 20 years. He is lucky enough to be sponsored but realizes everyone can't be.

GRIP AND SLIPPAGE

Ty constantly experiences slipping when surfing. This was one of the largest learning curves when he started surfing.

BUOYANCY AND WEIGHT

Ryan recently lost his prosthetic leg in the ocean while surfing. Since he couldn't find it he had to get a new leg and foot.



COST

For Fabrizio, cost has always been a struggle. He uses an old prosthetic foot, wrapped in tape and a pool noddle to keep it afloat if it were to fall off.

Market Insights

EVERYDAY PROSTHETICS

Current prosthetics for everyday use allows no or very little adduction and abduction movements.

Ossur

Pro-Flex® XC

Pro-Flex XC prosthetic foot is designed for hiking and jogging, as well as walking on level ground.

$$$$

Not Waterproof

Limited adduction and abduction

Ossur

Flex-Foot Balance®

Flex-Foot has 8 degree Dorsiflexion and Plantar flexion

$$$$

Not Waterproof

No adduction and abduction

College Park

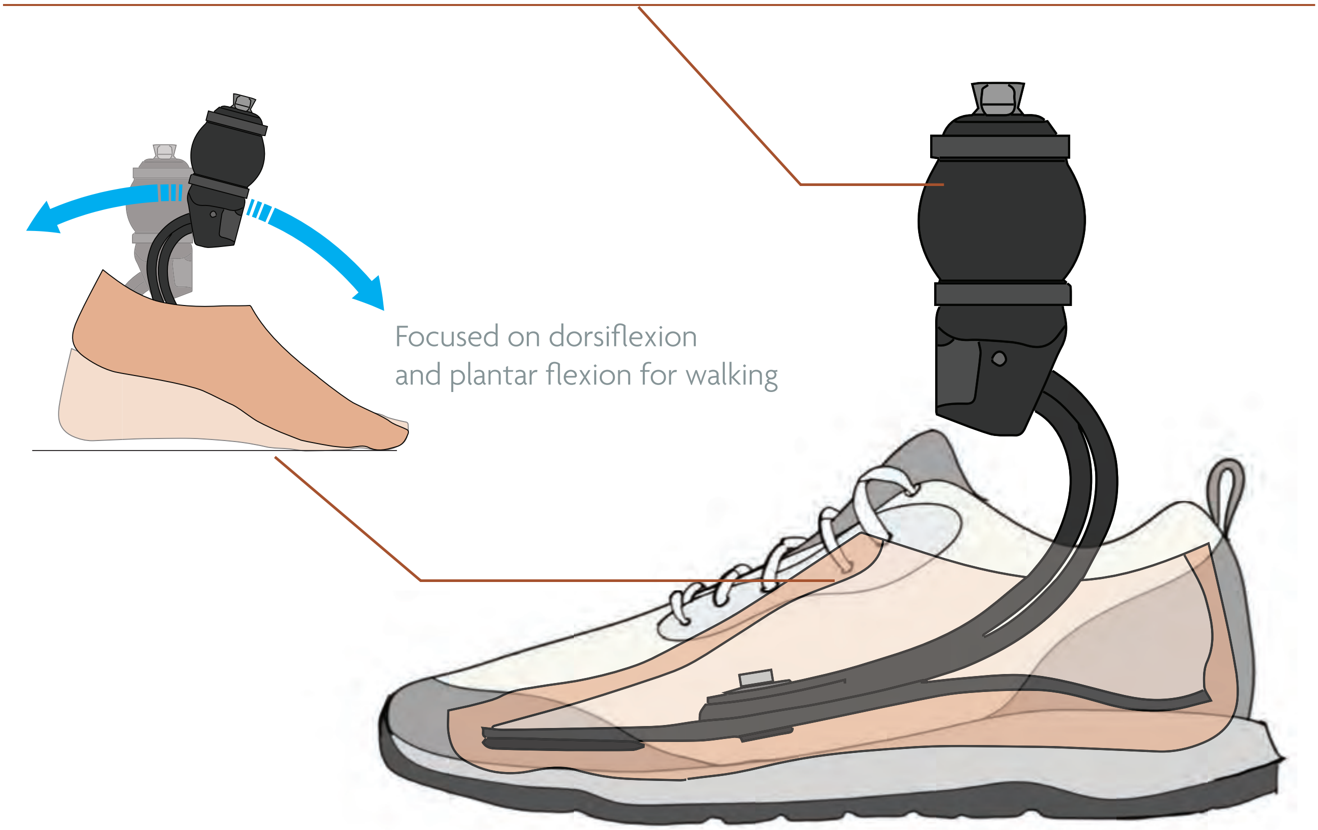
Trustep

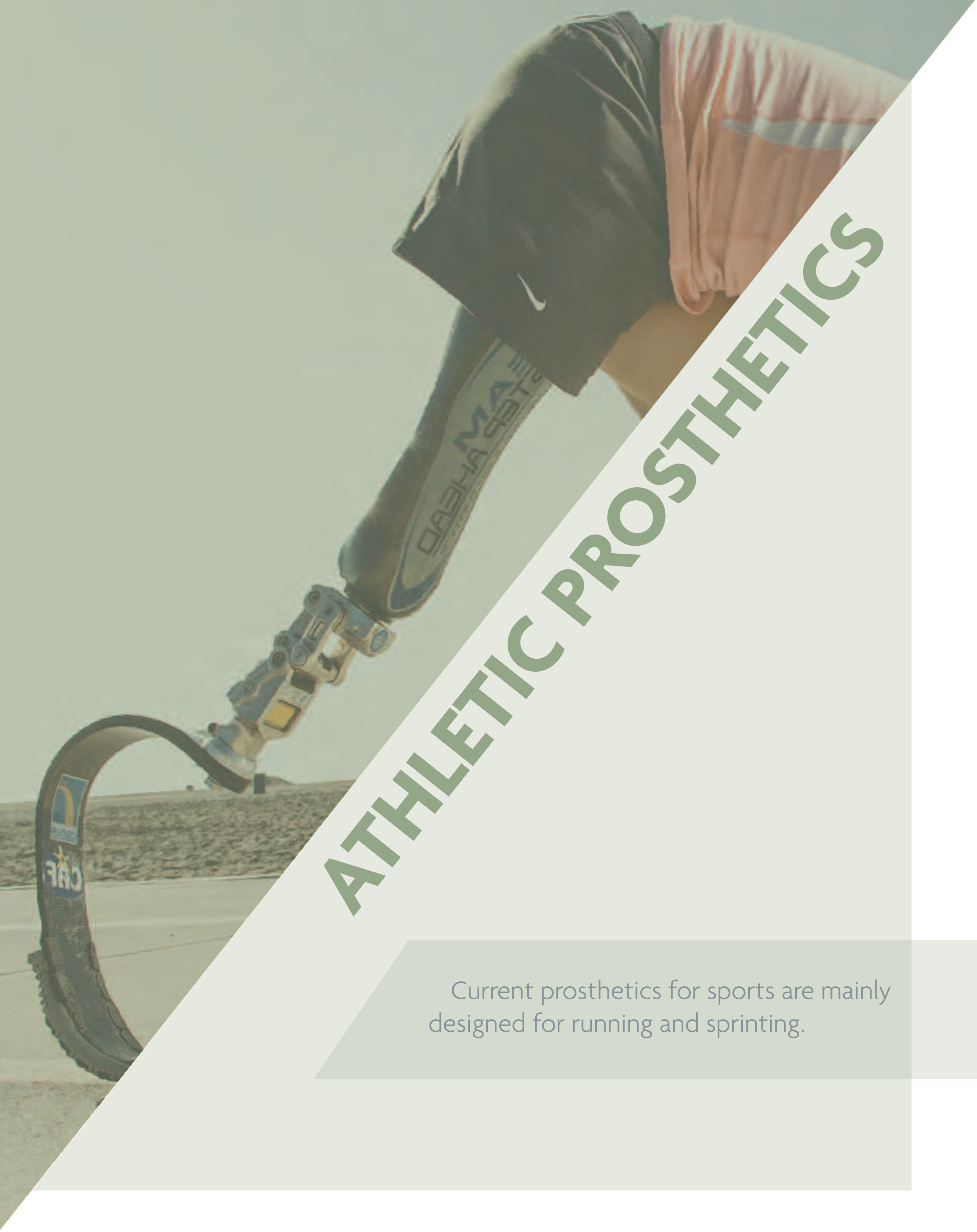
Trustep is a multi-axis Prosthetic foot for walking adult

$$$$

Not Waterproof

Limited adduction and abduction





ATHLETIC PROSTHETICS

Current prosthetics for sports are mainly designed for running and sprinting.

Ossur
Cheetah Xtreme
Cheetah Xtreme is designed specifically for the fast, short-distance sprints.

Waterproof

No adduction and abduction

Ottobock
Fitness prostheses
Ottobock's Fitness prostheses is designed for different levels of workout and especially for running.

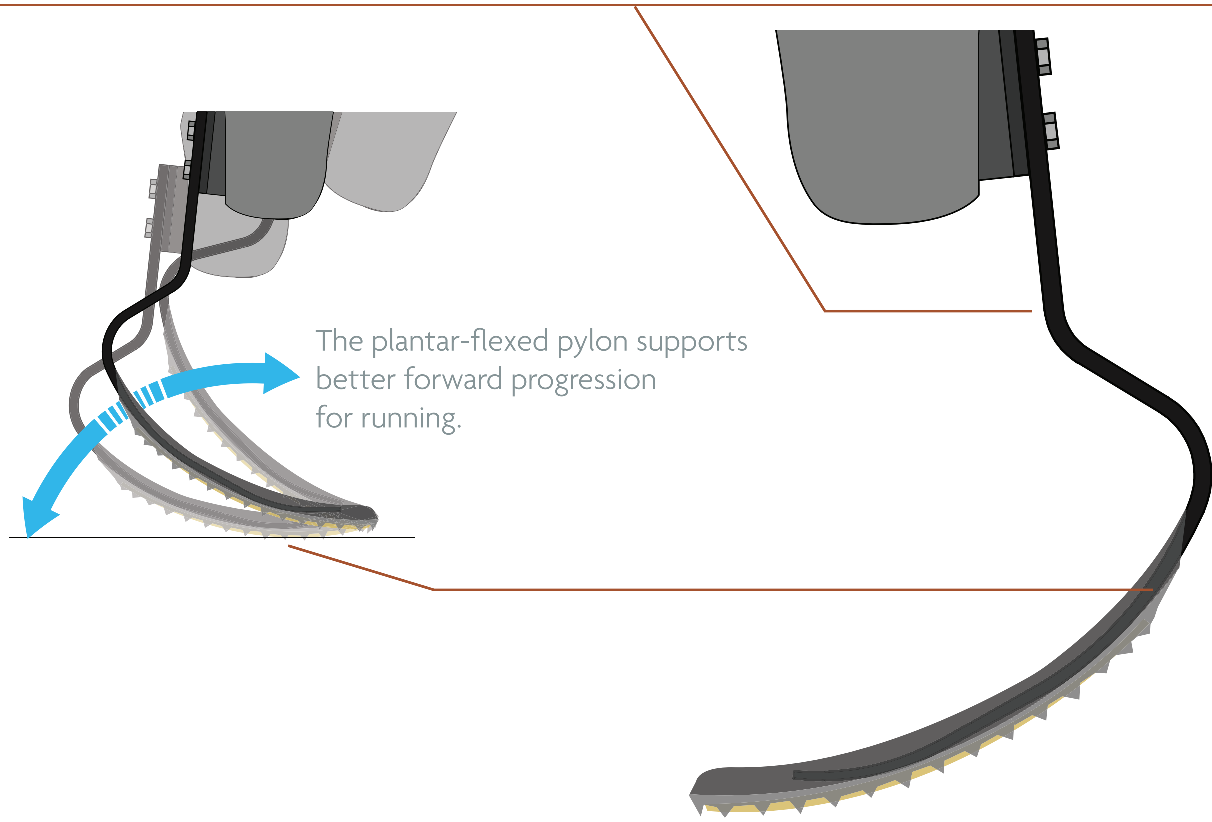
Water Resistant

No adduction and abduction

Freedom Innovations
Slalom Ski
The Slalom Ski Foot is designed to be quickly and easily inserted directly into a ski binding.

Water Resistant

Limited adduction and abduction



WATER PROSTHETICS

Current prosthetics for water activities are either too expensive or don't adapt to surfing.

RUSH

The RUSH Foot H2O

The RUSH Foot H2O is water resistant and provides traction on slick surfaces.

$$$$

Water Resistant

Limited adduction and abduction

Ottobock

Taleo

Taleo provides smooth rollover for walking and 18% water resistant

$$$$

Water Resistant

Limited adduction and abduction

Freedom Innovation

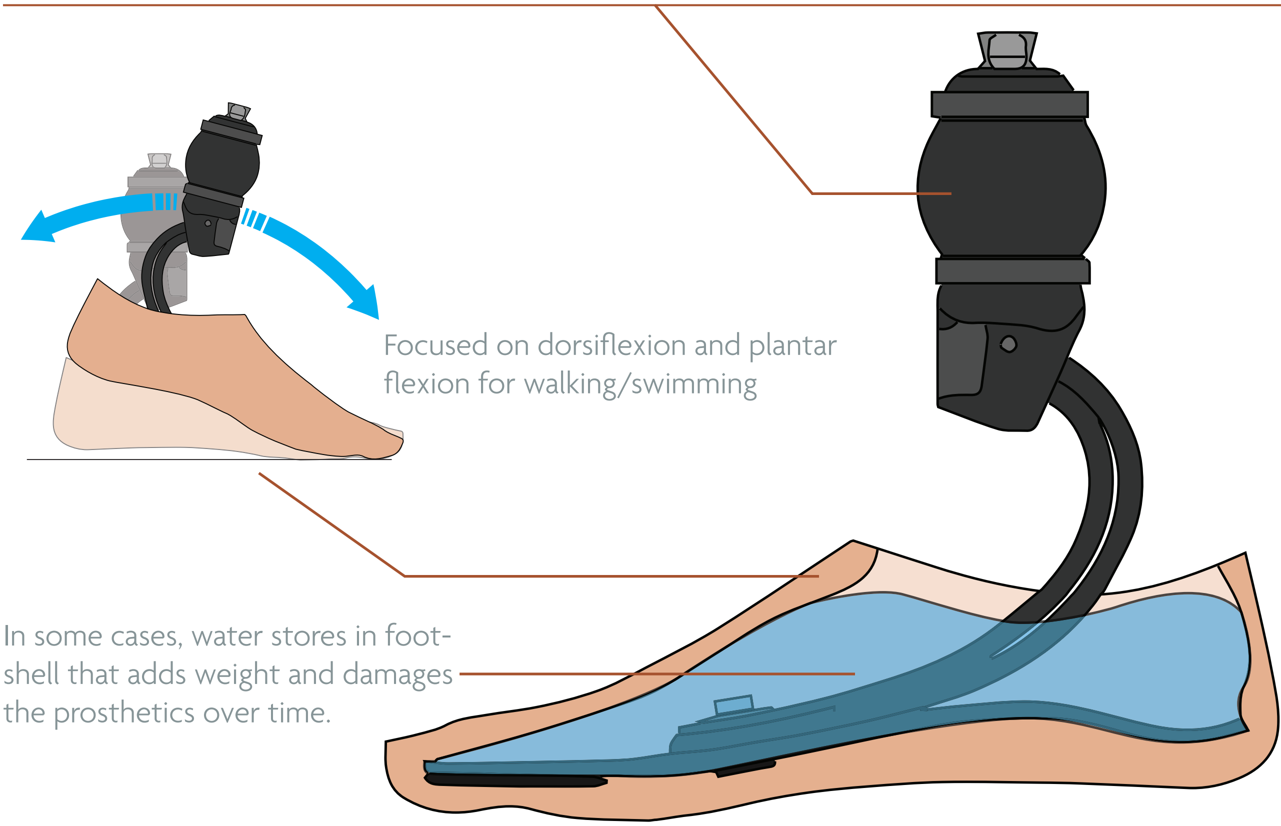
Freestyle Swim

It is designed for swimming. The ankle can be moved to 70° plantar flexion for swimming.

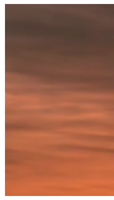
$$$$

Water Resistant

Limited adduction and abduction



HOME BREWED COMPROMISES
AREN'T SOLUTIONS

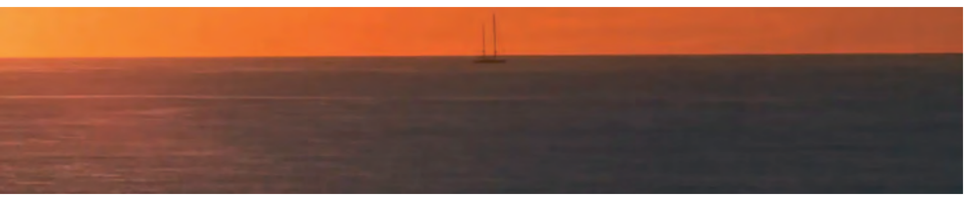


Recreational or 'cosmetic' legs aren't covered by insurance, even if it provides a significant increase to the person's quality of life. This leads to lots of home brewed solutions. The current solution amputee surfers turn to typically is using an old leg, tape, and rubber sleeves.

> "After a short while however, the prosthesis started falling apart, piece after piece. Every day I had to repair it, using whatever piece of equipment and tool I could find."
>
> *-Fabrizio Passetti,*
> *Right BK Amputee Surfer, Italy*

Ty Tuckets surfing leg: an old leg wrapped in tape to prevent rusting inspired by another amputee surfer online

Frabrizio's leg is a combination of parts, all wrapped in duct tape holding it together.



OUR MEDICAL TEAM

We assembled a group of medical and sports professional to connect us to athletes and help us understand the world of prosthetics.

Bob Babbit

Co-Founder of Challenged Athletes Association

Bob connected us with athletes early on through the foundation. He would also provide other internal connections later on.

Travis Ricks

Challenged Athletes Association

Travis, an amputee himself, talked with us about the cost of prosthetics, grants and how he helps athletes get the equipment they need for their sports.

AlliedOP Prosthetics and Orthotics

Prosthetic Clinic

Supplied us with the standard pylon and male pyramid connector.

Kevin Loughry

Prosthetist and Orthotist MedEast

Kevin discussed with us various mounting methods as well other aspects to prosthetic devices.

Chris Grimes

Physical Therapist, Jersey Shore University Medical Center

Chris has experience volunteering at several adaptive surfing events. With this and his background, he was able to address questions we had about the functions of the human foot and ankle.

Adam Deskevich

Materials Engineer and Specialist, Knoll

Adam discussed with us various material options we could use based on the extreme elements our device would be subjected to.

IV DESIGN CRITERIA

ESTABLISHING GOALS

We created a set of goals that we would then follow throughout the project. This included performance criteria, anecdotal suggestions and plans to test the final product in the water with our surfing network.

THE GOAL

Our goal is to instill confidence and independence to lower limb amputees who participate in surfing and create new affordable opportunities for those who have recently experienced an amputation.

Design a low-cost waterproof prosthetic foot with increased ankle mobility to enable correct surfing mechanics.

THE CRITERIA

“The largest struggle is not having the range of motion in the ankle as you would with a real foot.”

- Ryan Johnson , Left BK Amputee Surfer, Virginia Beach

1 INCREASED RANGE OF MOTION

Our foot needs to be effective in recreating the ROM of a human ankle, allowing it to lay flat on the surf board, providing the most grip and balance.

2 POP-UP FLEXIBILITY

Second, it needs to be flexible enough to preform a proper pop-up, yet stiff enough to not affect walking.

“My foot is at an angle, instead of maximum contact, so it slips off the board, during the pop-up.”

- Dana Cummings, Left BK Amputee Surfer, California

"My foot shell would pool up with water, so I drilled holes into it to act as a drain."

-Ty Tucket, Left AK Amputee Surfer, California

3 ABILITY TO DRAIN

Thirdly, the foot cannot hold any water (or sand) it may come in contact with. It needs to be hydrodynamic and wick away water.

4 LONG LIFESPAN

Lastly, it needs to be built for its environment and continually last after several months of use.

"I changed the leg/foot because it started to deteriorate due to the effects of saltwater and sand."

-Ty Tucket, Left AK Amputee Surfer, California

PERFORMANCE BENCHMARKS

Each criterion also had a performance requirement we had to consider. If we wanted our prosthetic, surpass the competition, it needed to perform just as well if not better.

FAMILIAR WEIGHT

Our device needs to be equal or weigh less than the existing prosthetic used for everyday activity.

UNIVERSALLY COMPATIBLE

Our device needs to be universally compatible with existing prosthetic mounting methods to ensure the most people have access.

ENHANCED GRIP

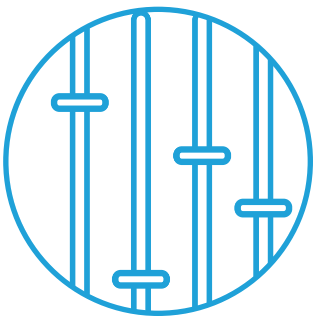
Surfers encounter several different surfaces on their way to the ocean. The device needs to grip both the surfboard and sand, minimizing slippage.

WATERPROOF

Our device needs be made from waterproof materials and hardware. Ideally hardware will not be exposed, further preventing corrosion.

TOUGHNESS

The device needs to fully support the weight and repetitive impact of an individual up to 350 lbs, without showing immediate signs of wear.

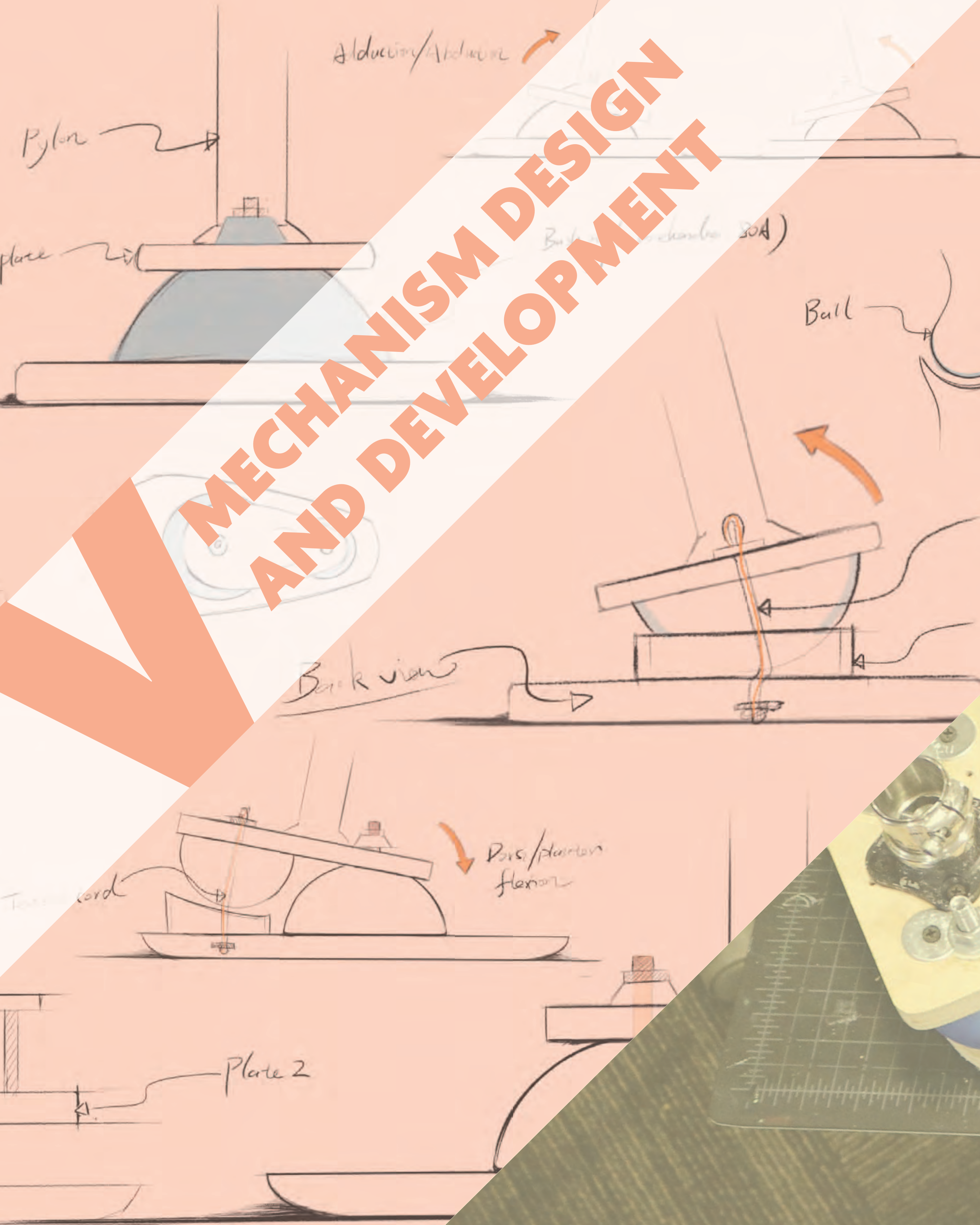


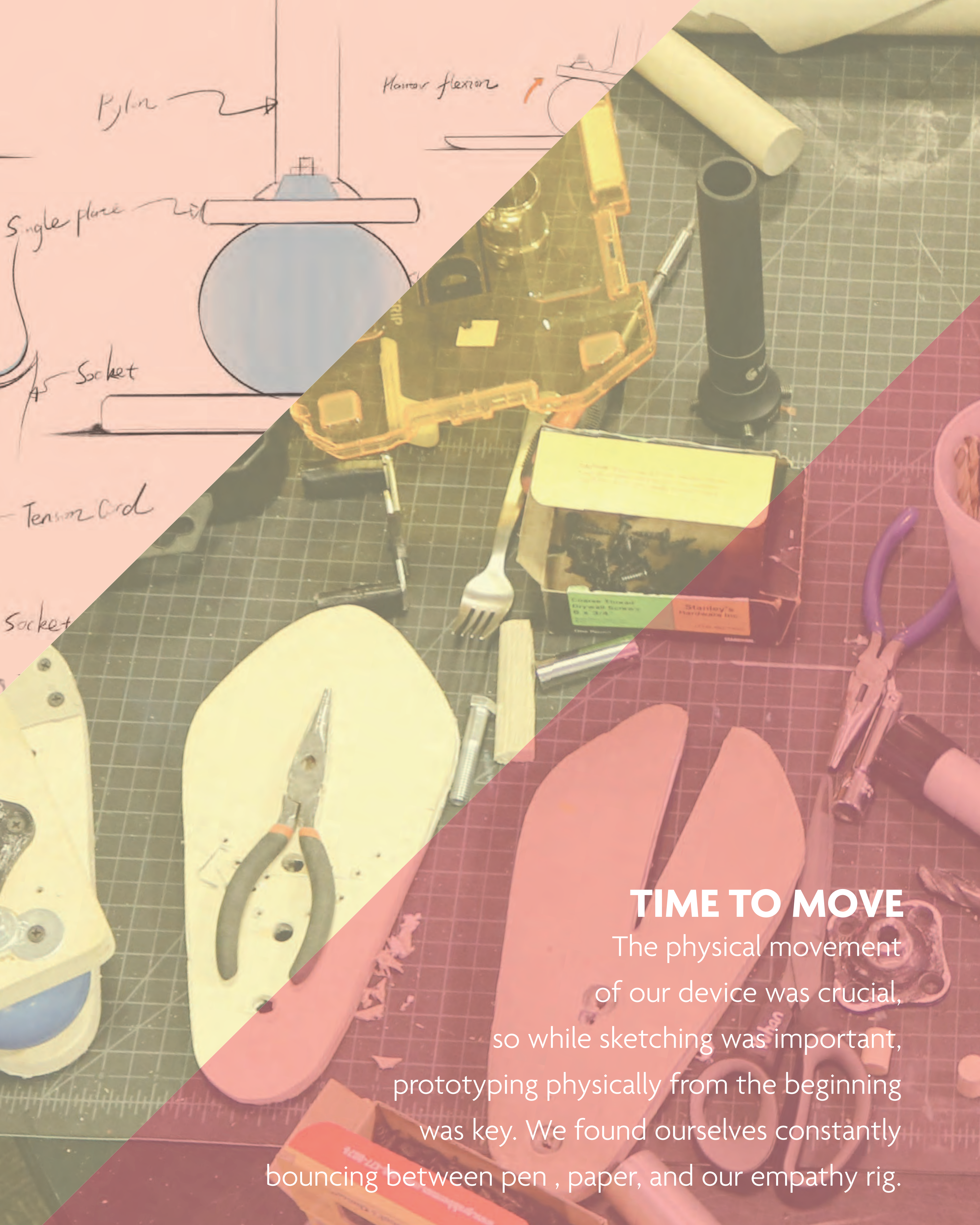
EASILY ADJUSTABLE

Prosthetics are extensions of the individual. Each person is different. Our device needs to have a level of adjustability.

V

MECHANISM DESIGN AND DEVELOPMENT





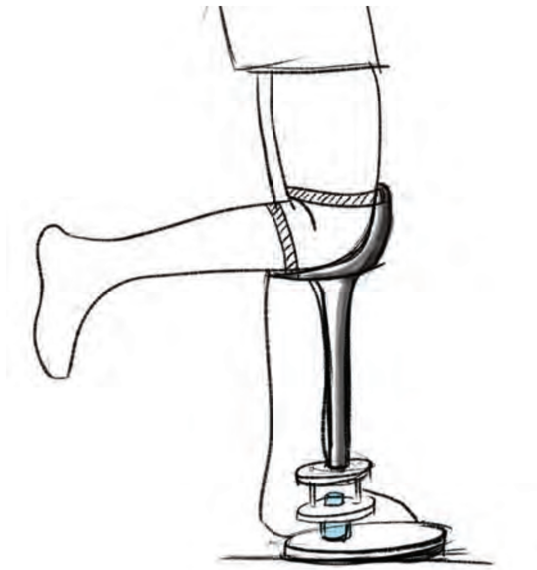
TIME TO MOVE

The physical movement of our device was crucial, so while sketching was important, prototyping physically from the beginning was key. We found ourselves constantly bouncing between pen , paper, and our empathy rig.

LEARNING TO EMPATHIZE

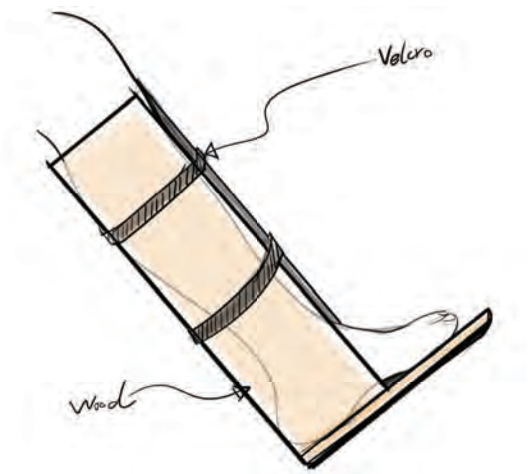
We knew that Lance was going to help us test our models, but it wasn't feasible to test everything with him, especially early on.

To combat this we were inspired by Tom Dair of **Smart Design** and their team when working on the project LIM. On the right is an early concept we explored.



Initial sketch for our empathy rig

Smart Design's empathy rig, simulating the sensation of the socket around the tailbone.



Wooden version of our empathy rig

VERSION ONE

Version one of the empathy rig was assembled using wood on either side to prevent our ankle from rotating. While this worked okay, we were experiencing some shifting that we thought could mislead us.

OUR "EMPATHY RIG"

For version two of the rig we modified an existing medical boot. Since these were already made to limit the motion it worked great. We also created a universal mount we could use on all of our models moving forward to streamline our testing.

We also had to add height to the other leg in order to walk properly. We did this by using blue foam and an extra shoe sole for grip.

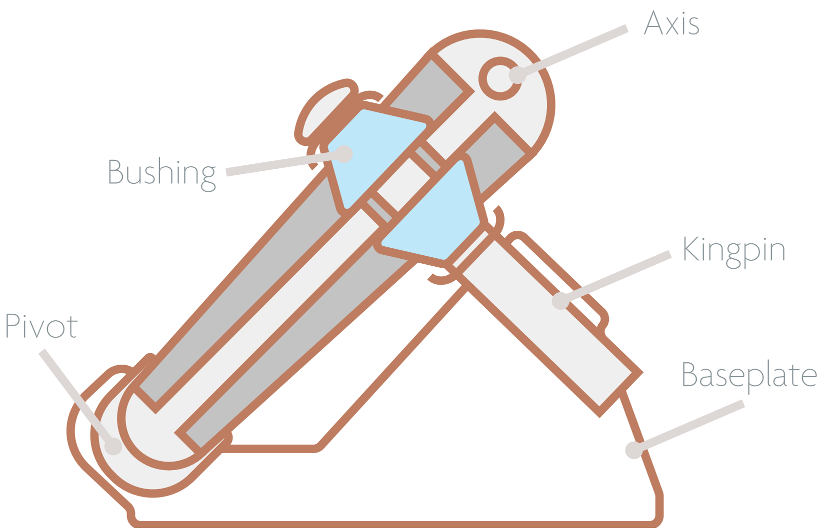
> "If your designing for someone who is blind, you might be able to close your eyes and imagine what it might be like to be blind... but you can't take your leg off."
>
> *-Tom Dair, Smart Design*

RECREATING THE ANKLE

While many prosthetics before us have recreated the movement in the ankle to some degree we needed to figure out a way to do so that was both waterproof and affordable to produce. We went through several phases of mechanism development before landing on our final solution.

One of our largest inspirations was the mechanisms of skateboard trucks. We had purchased a “Surfing Skateboard Kit” for testing, but when we went to install it we saw how the bushings were mounted and allowed for a wide degree of articulation.

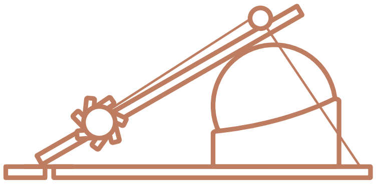
Surfing Skateboard Adapter



Skateboard Truck Diagram

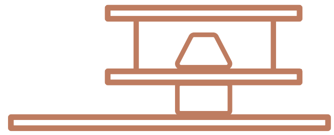
MECHANISM EXPLORATIONS

1



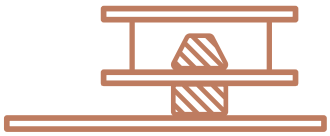
Ball "Bushing" with Ratchet Shock Cord

2



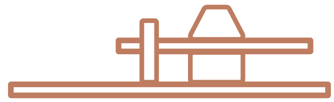
Single Axis 100A Bushings

3



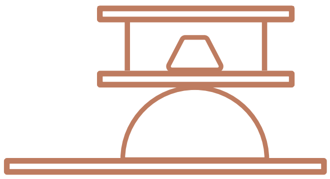
Single Axis 80A Bushings

4



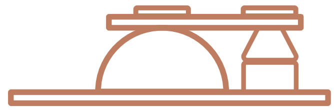
Single Axis 80A Bushings With Rotational Stopper

5



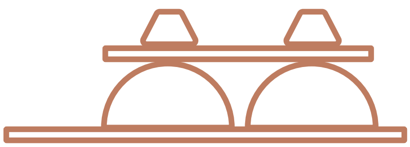
Single Axis Semi-Sphere "Bushing" with 80A Topper

6



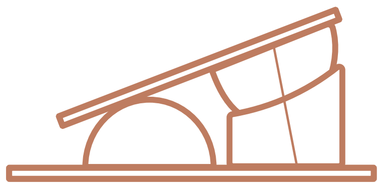
Dual Axis 80A Bushings And Semi-Sphere "Bushing"

7



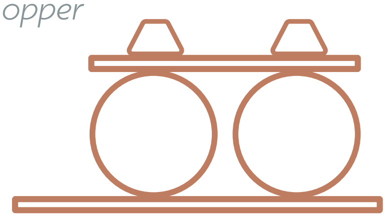
Dual Axis Semi-Sphere "Bushings" with 80A Topper

8



Dual Axis Reverse Semi-Sphere with Shock Cord

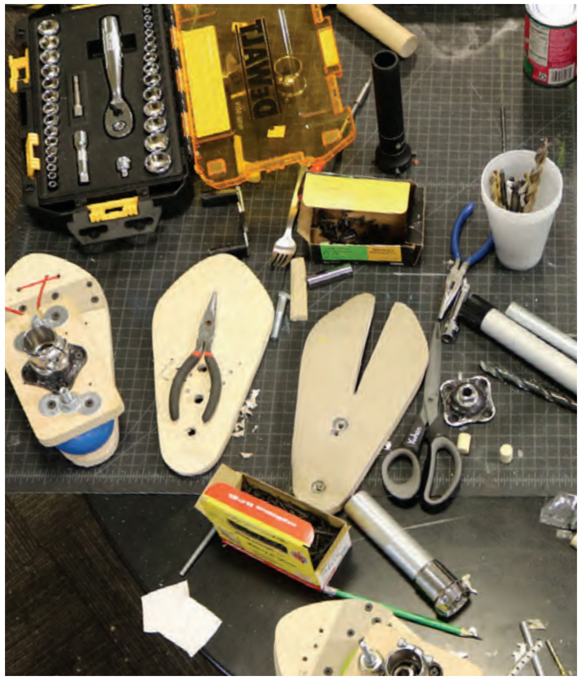
9



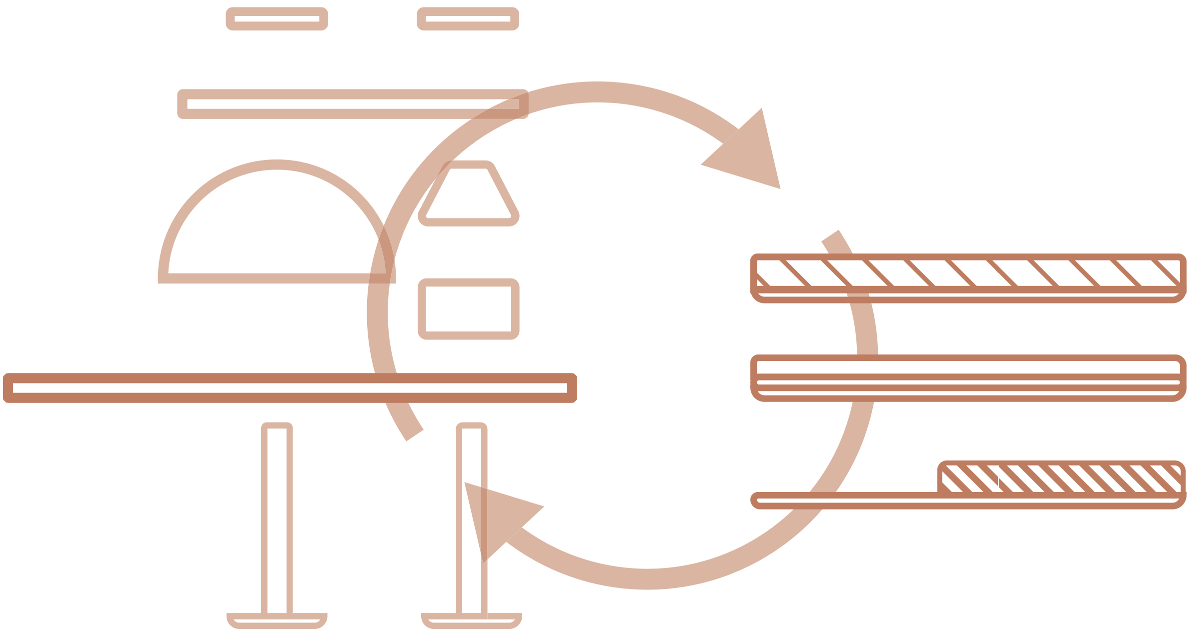
Dual Axis Ball "Bushing" with 80A Topper

NARROWING DOWN
A FOOTPRINT

While we were developing the initial 9 mechanisms, we were also exploring a variety of footprint shapes. We designed the models to be as modular as possible. This allowed us to swap various parts of the models for quick testing and iteration. This also allowed us to see what parts of the design were more crucial than others. We also got an understanding for what hardware worked and what didn't.



Swapping parts to various models

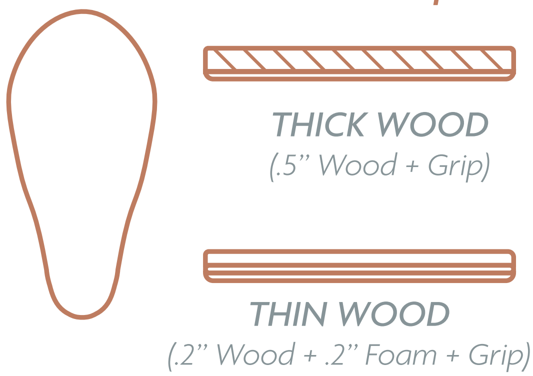


Designing the models to be modular allowed for easy iteration

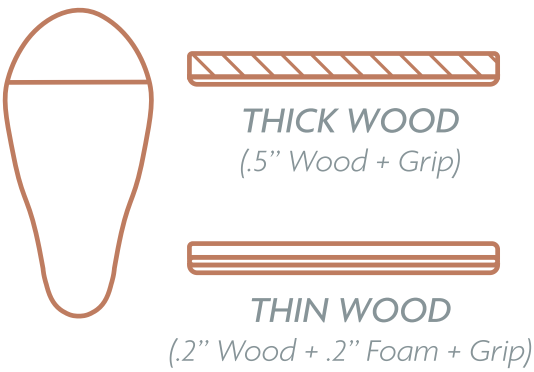
FOOTPRINT EXPLORATIONS

1 Left Footprint

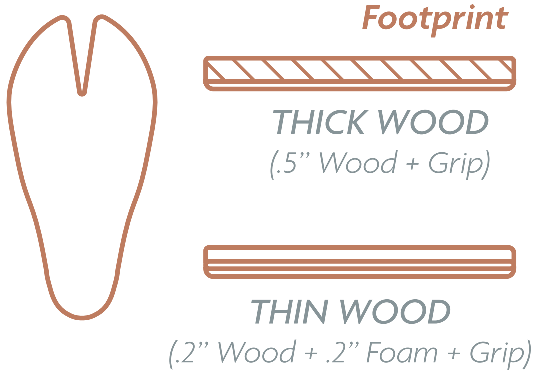
2 Combination Footprint



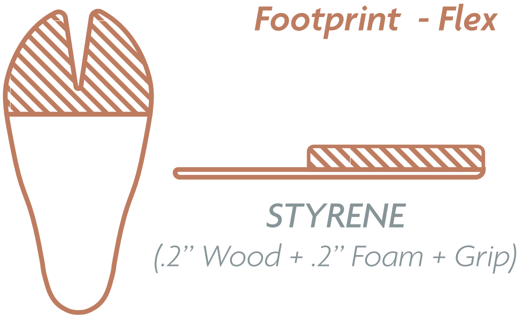
3 Combination Footprint - Flap



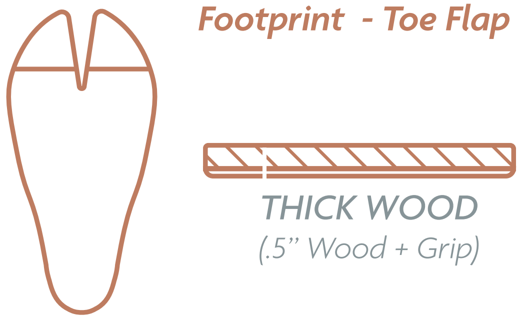
4 Combination Camel Toe Footprint



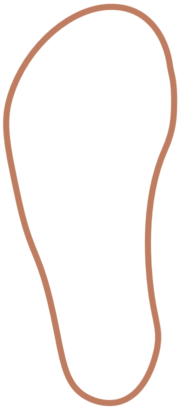
5 Combination Camel Toe Footprint - Flex



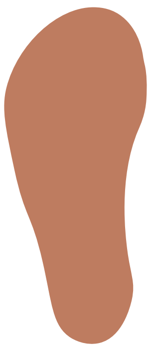
6 Combination Camel Toe Footprint - Toe Flap



SINGLE SIDE

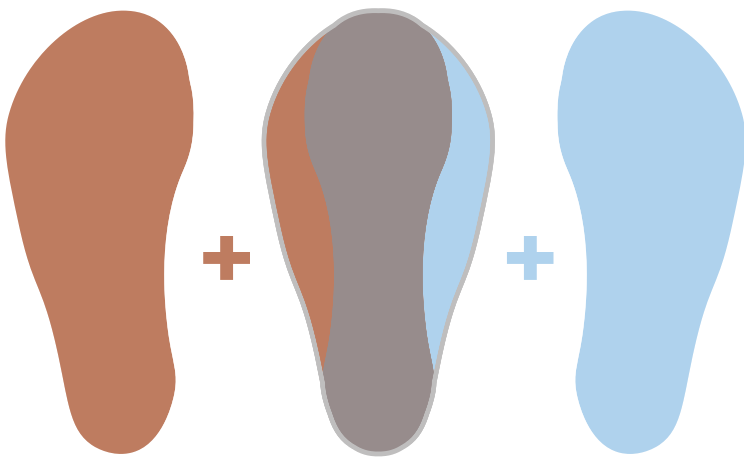


Everyone surfs a little different. Because of this, we had to consider both a left and a right footed model for the device. However after some initial tests we decided it would be worth exploring an ambidextrous option for both balance and cost.



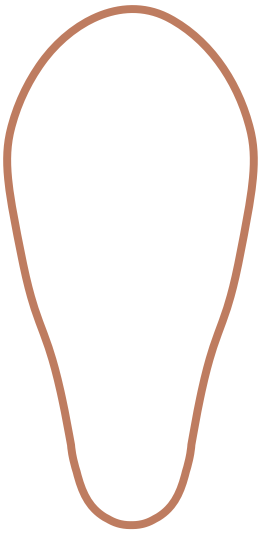
GOOFY
(Left Foot Forward)

REGULAR
(Right Foot Forward)



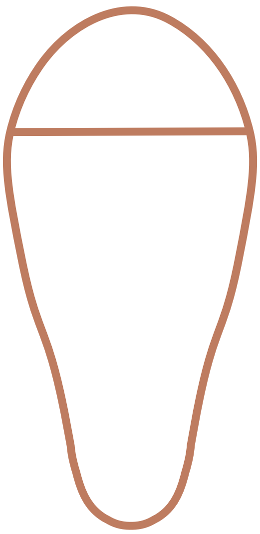
With one model for both feet accessibility could be increased, while cost could be lowered.

COMBINING FEET



+ Equal balance on either side

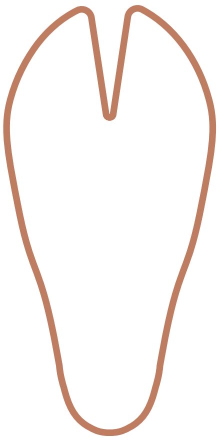
− Larger than normal foot



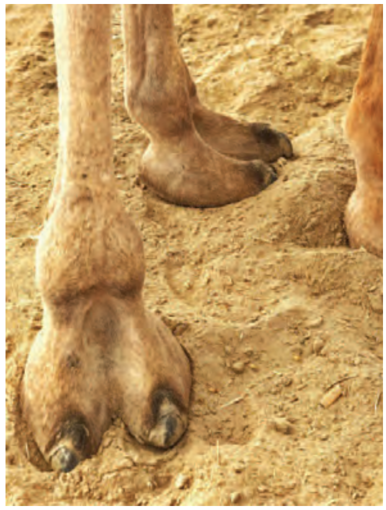
+ Simulates front bending of toe

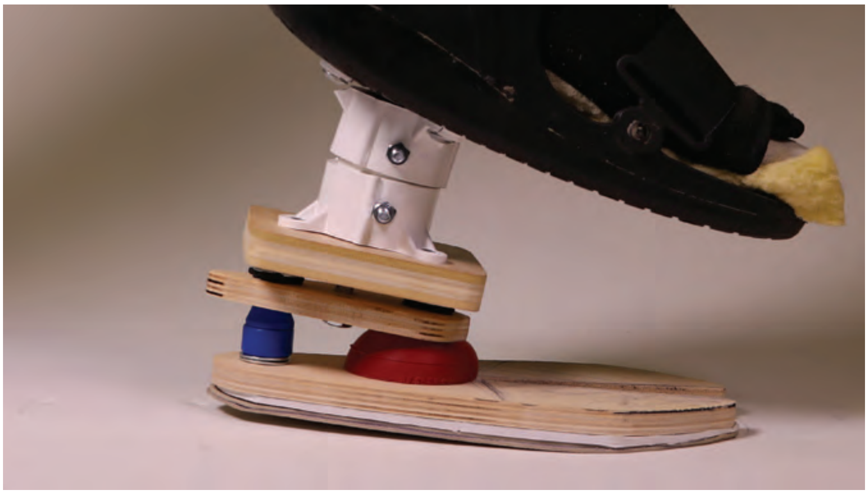
− Makes foot feel short

THE CAMEL'S FOOT



Camels are one of the only animals who walk long distances across the sand. This inspired us to **look into their anatomy** and combined it with our ambidextrous solution.

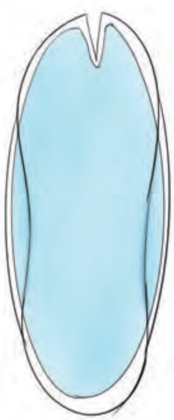


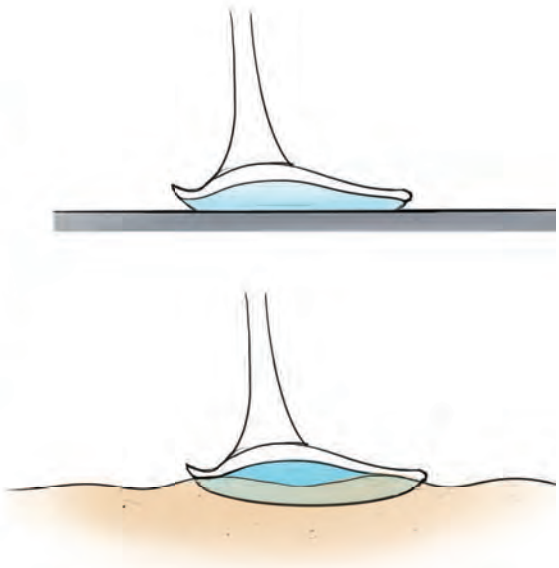


Split toe aided in adduction and abduction motion

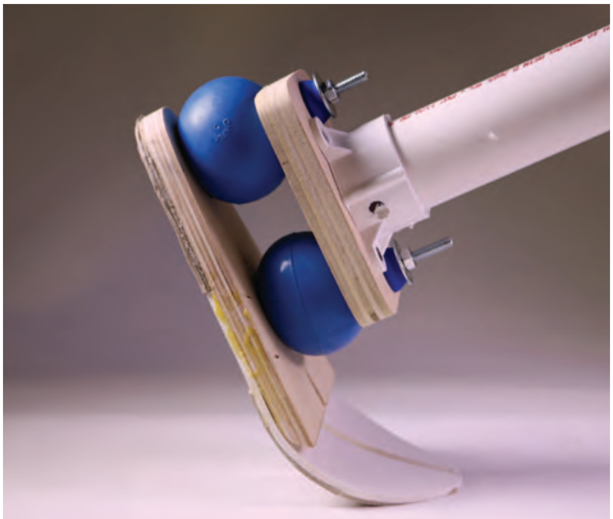
Lots of weight caused the form to split down the center

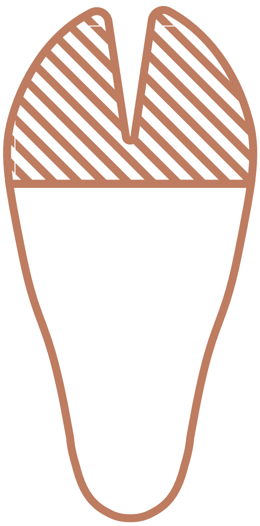
One thing that helps camels walk across the sand is a **pad of fat** on the underside of the foot. We considered how we could integrate this into our designs. Early iterations had us taping butt pads to the bottom of our feet.





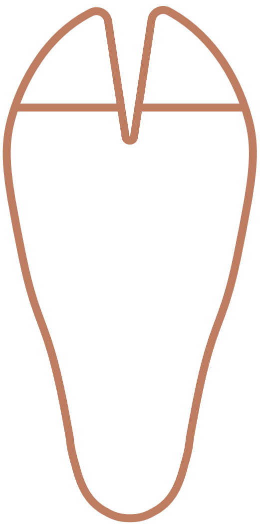
VARIATIONS OF THE CAMEL'S FOOT





+ Simulates plantar and dorsiflexion

− Body weight proves this provides too much flex

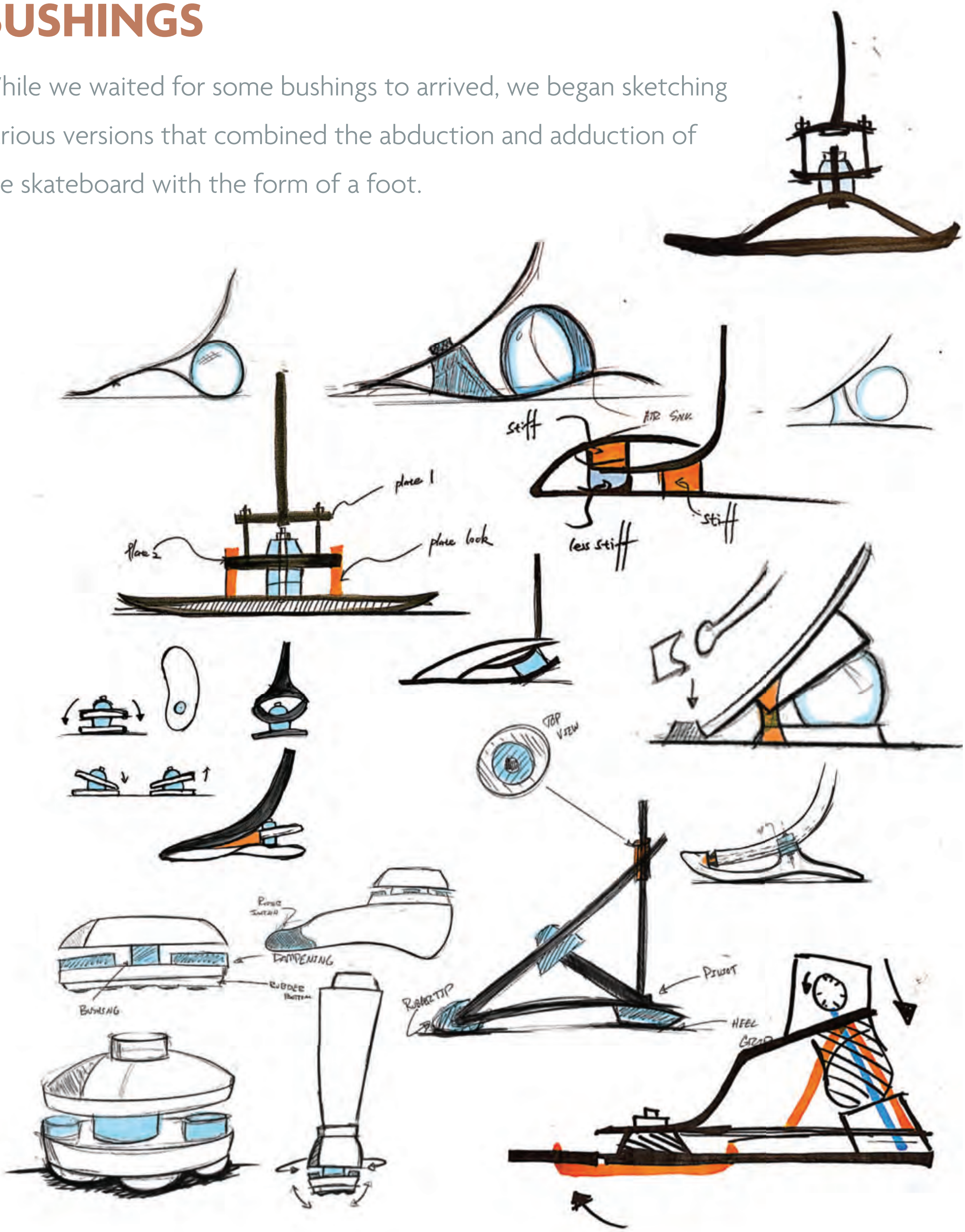


− Little benefits provided

After testing all of the concepts in several variations with all 9 mechanisms, we decided that the best performance was coming from the standard combination shape. This is the shape we **tested with Lance.**

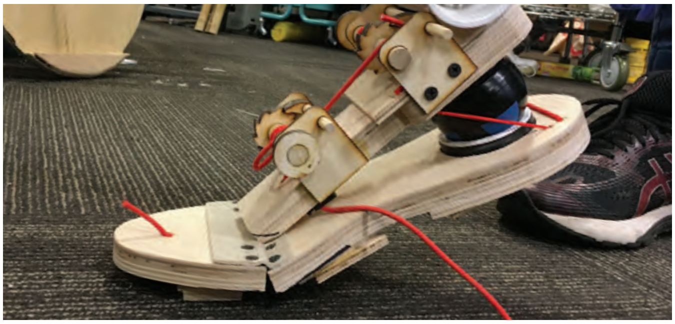
EXPLORING WITH BUSHINGS

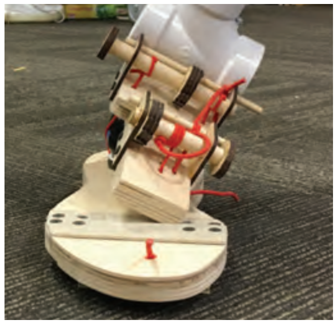
While we waited for some bushings to arrived, we began sketching various versions that combined the abduction and adduction of the skateboard with the form of a foot.



MECHANISM 1

Ball Bushing with Ratchet Shock Cord





+
1. Ball and socket joint provides good articulation
2. Shock absorption of the sphere could be felt

−
1. Para-cord ratchet system was complicated
2. Not structurally sound (brittle)

MECHANISM 2

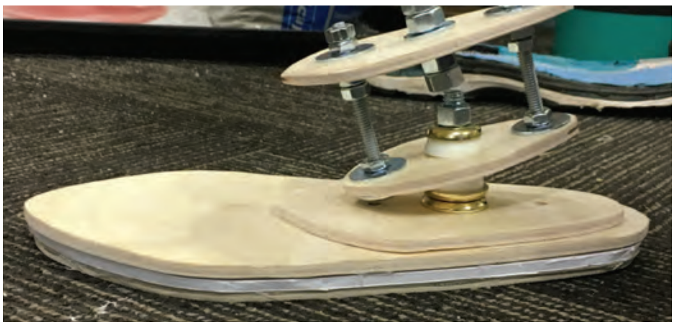
Single Axis 100A Bushings

+
1. Conceptually the concept works

−
1. Adding body weight shows not stiff enough

MECHANISM 3

Single Axis 80A Bushings

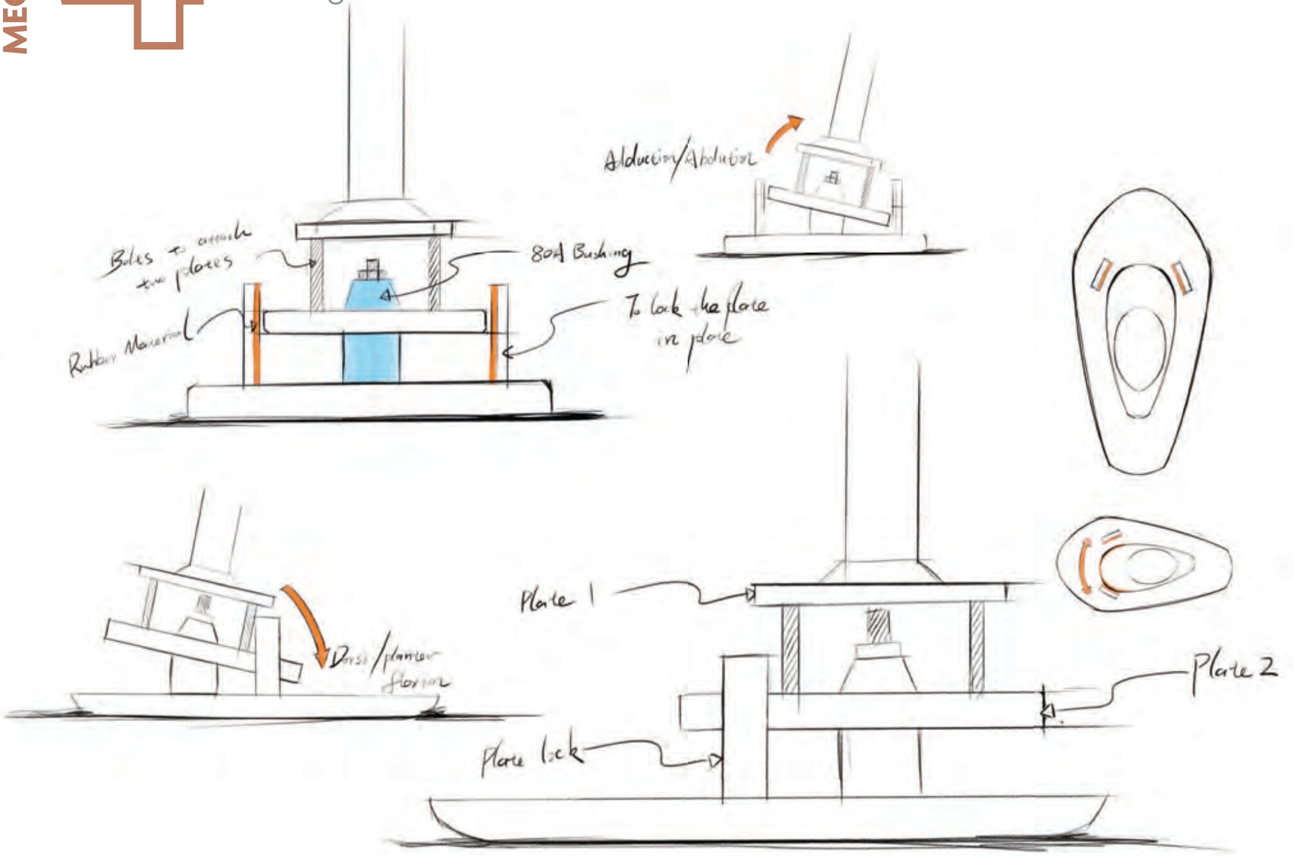


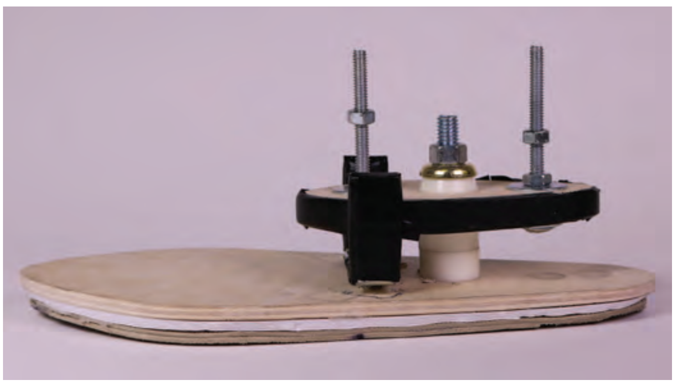
+
1. 100A proves to be much stiffer

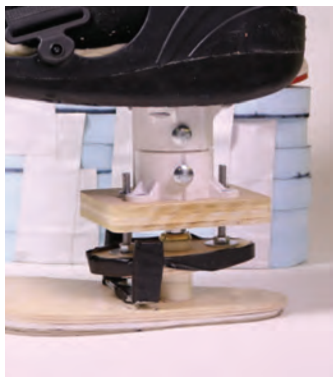
−
1. Not stiff enough
2. 360 degrees of rotation

Single Axis 80A Bushings With Rotational Stopper

Since the initial bushing concept showed some potential we began iterating off this idea and created our fourth model.







+

1. The stopper in the front stopped the rotation
2. 100A stiffness felt strong

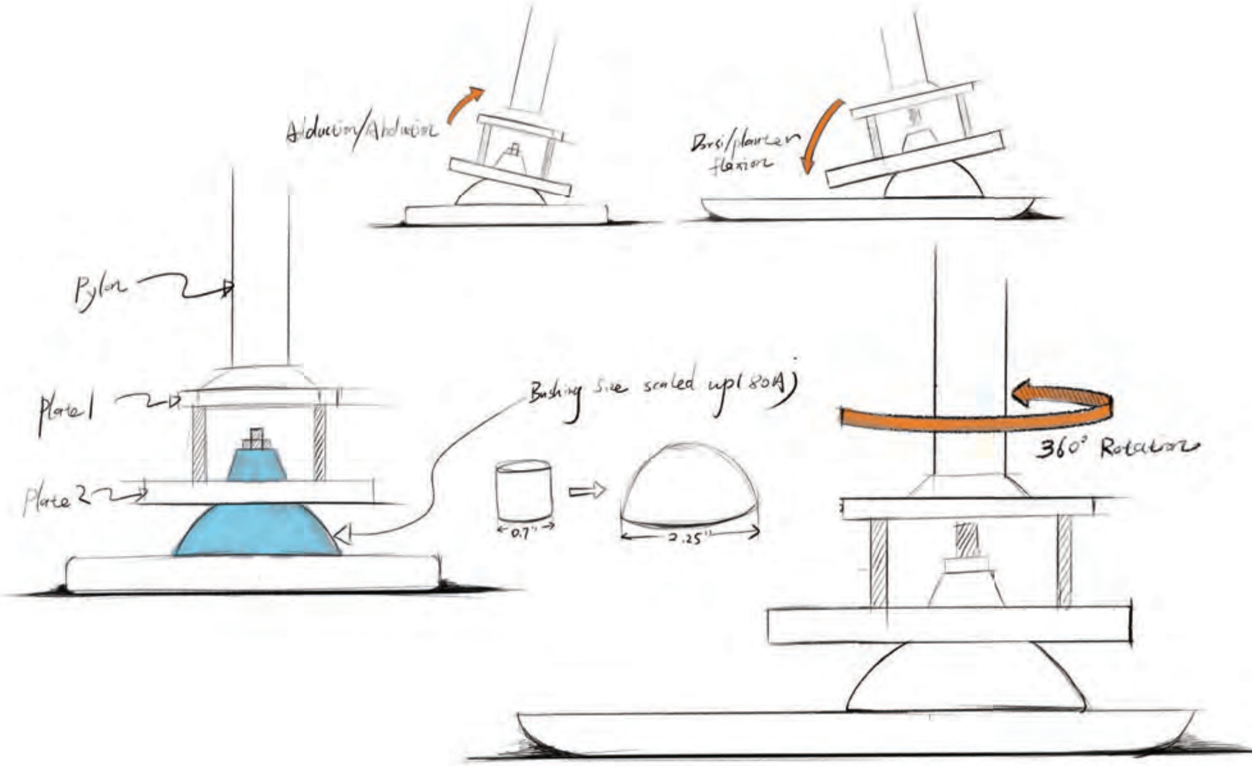
−

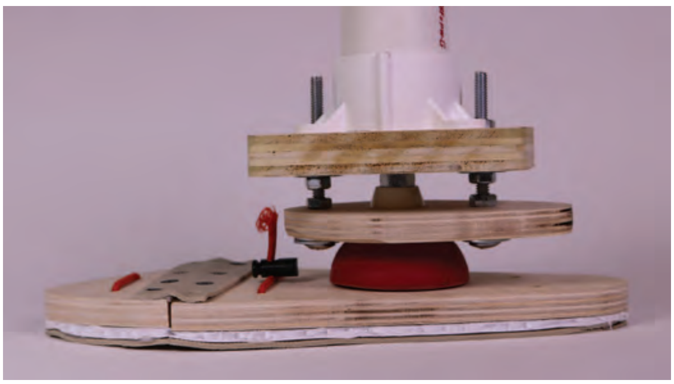
1. Abduction and adduction motion had no limit
2. Single axis didn't offer enough support

MECHANISM 5

Single Axis Semi-Sphere Bushing with 80A Topper

To limit the abduction and adduction motion we built upon the single axis and expanded the surface area of the bushing, hence the semi-circle.



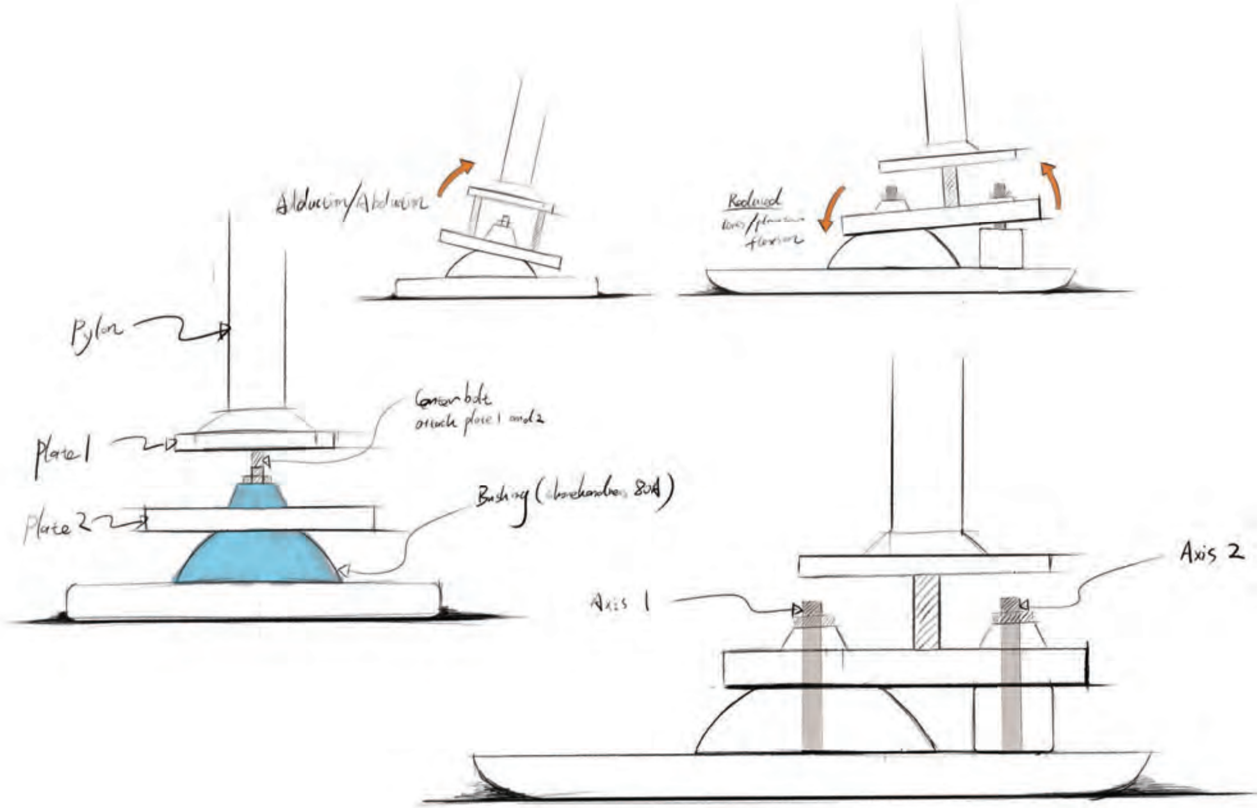


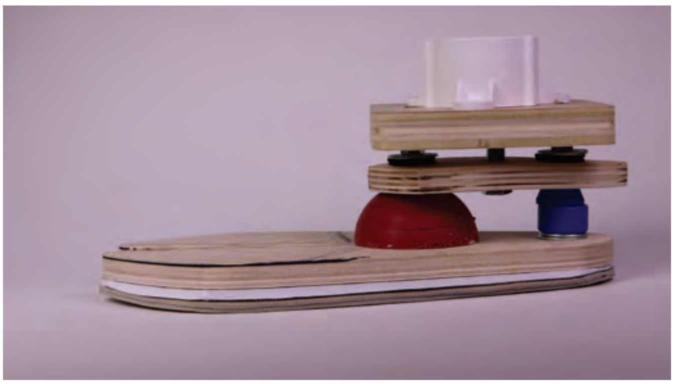
+	1. Larger bushing helped with shock absorption when stepping 2. Created uniform tilt in all directions (360 degrees)	−	1. The semi-sphere shape encouraged too much tilt 2. No way to adjust the stiffness of the joint

MECHANISM 6

Dual Axis 80A Bushings And Semi-Sphere Bushing

Since the single axis was providing too much movement, we added a second axis and combined the fourth and fifth concepts.



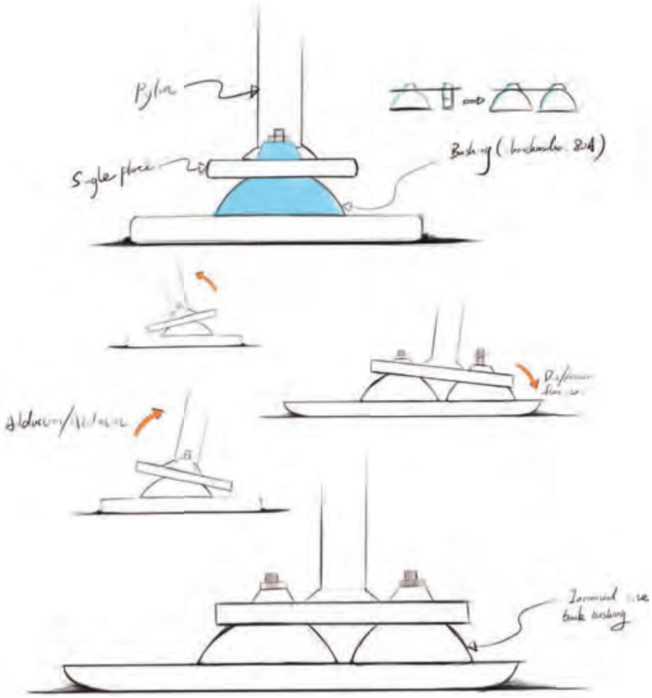


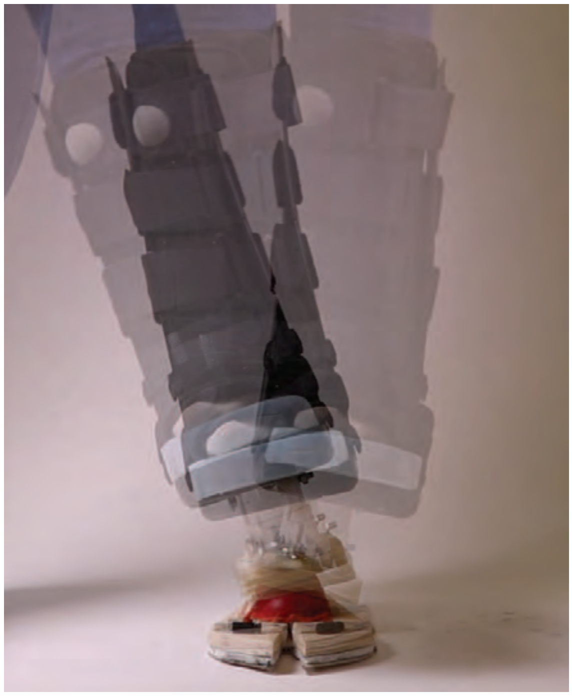
+ 1. Dual axis eliminates rotation 2. Lateral walking felt very secure 3. Tightening helped the stiffness	− 1. Abduction and adduction still felt loose 2. Not easy to tighten

MECHANISM 7

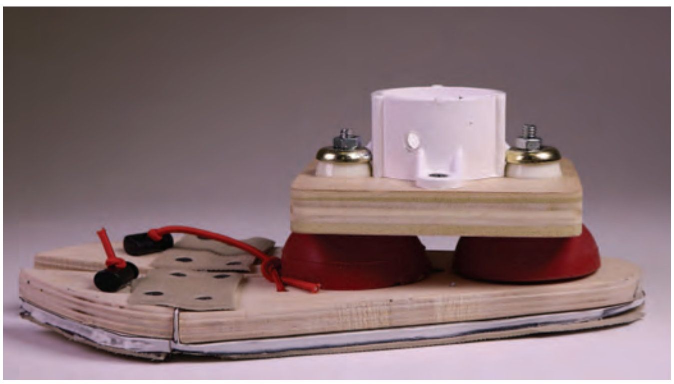
Dual Axis Ball Bushing with 80A Topper

Since six was still too loose we doubled up on the semicircles, while keeping the back axis. More surface area was the goal here.





Larger range of motion can be seen

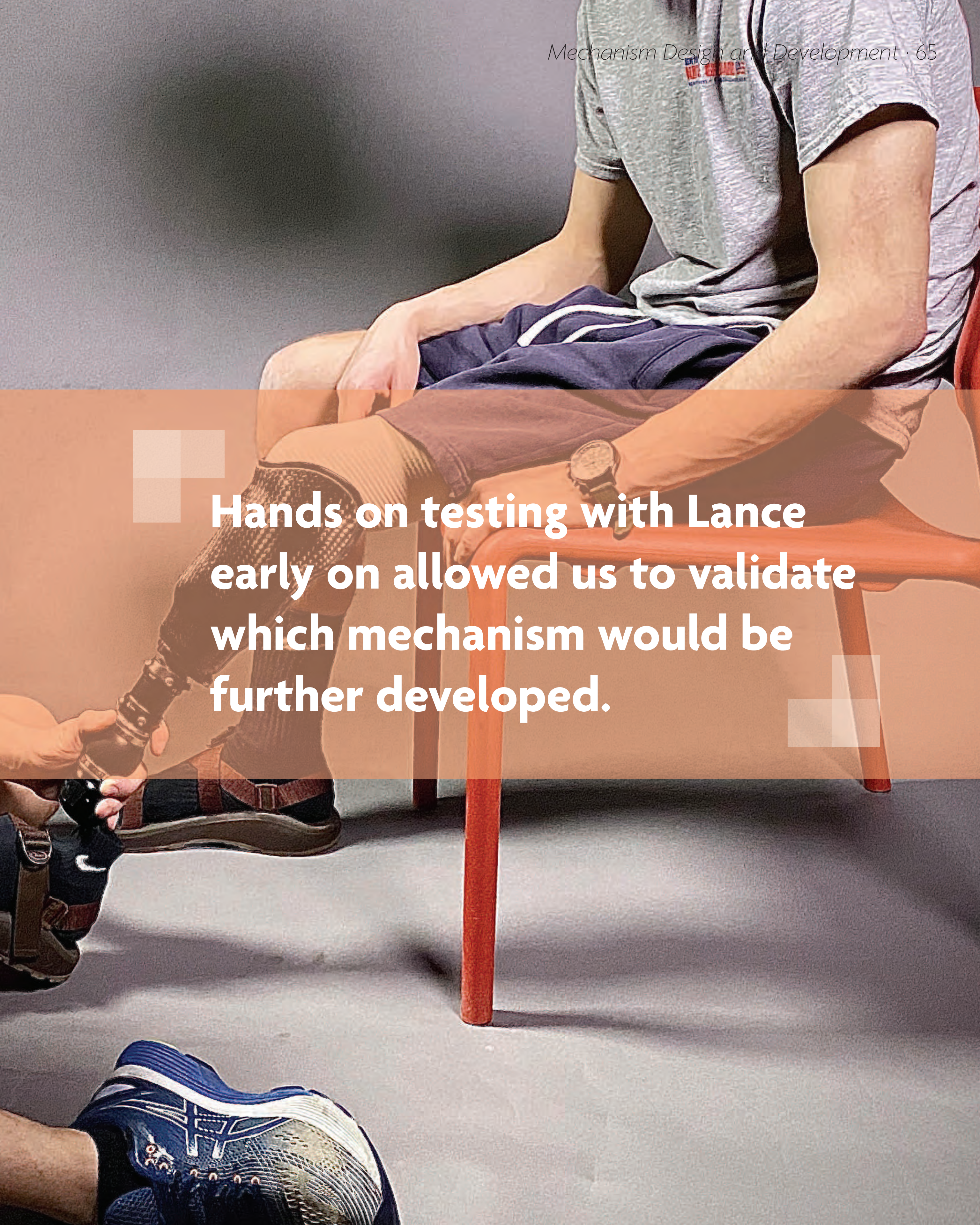


+ 1. Dual axis eliminates rotation 2. Lateral walking felt very secure 3. Easy access to tighten	− 1. Abduction and adduction tilted too quickly 2. The curvature of the top creates too much tilt

TESTING WITH LANCE
TRIP ONE

In order for us to test with Lance our models had to be safe. We established safety benchmarks that we needed to hit, which we first testing on ourselves with our empathy rig. We also needed to establish criteria to ensure Lance's safety since he was going to be relying on it to walk. We discussed our progress with him while we tested on our empathy rig and when we had something that felt right we invited him to test. The last two concepts (8 and 9) were tested with Lance.

THE BENCHMARKS

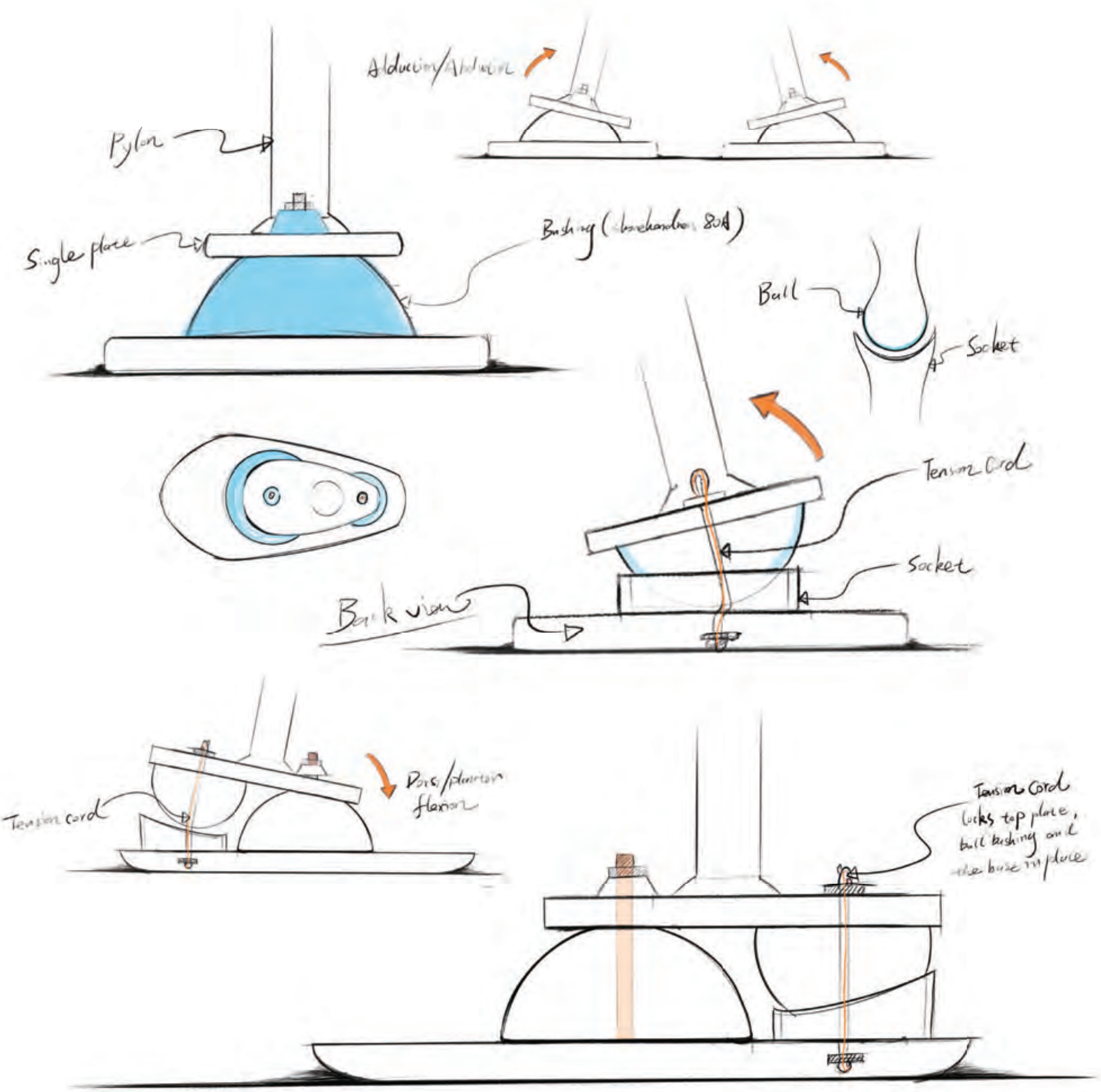


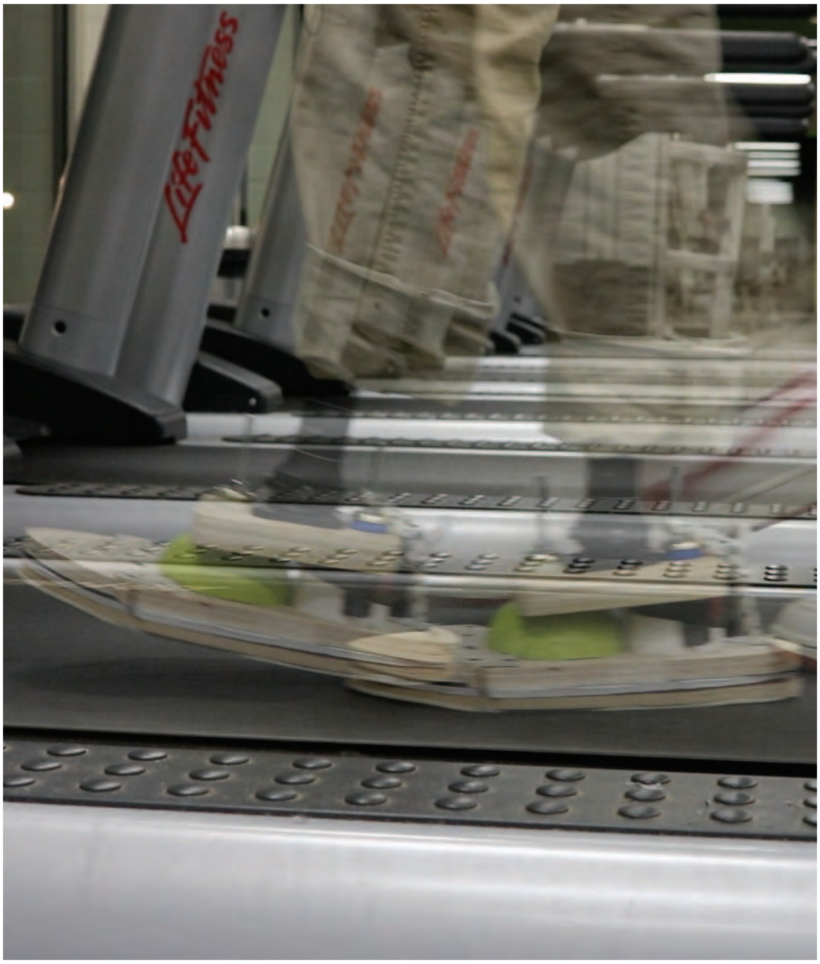
Hands on testing with Lance early on allowed us to validate which mechanism would be further developed.

MECHANISM 8

Dual Axis Reverse Semi-Sphere with Shock Cord

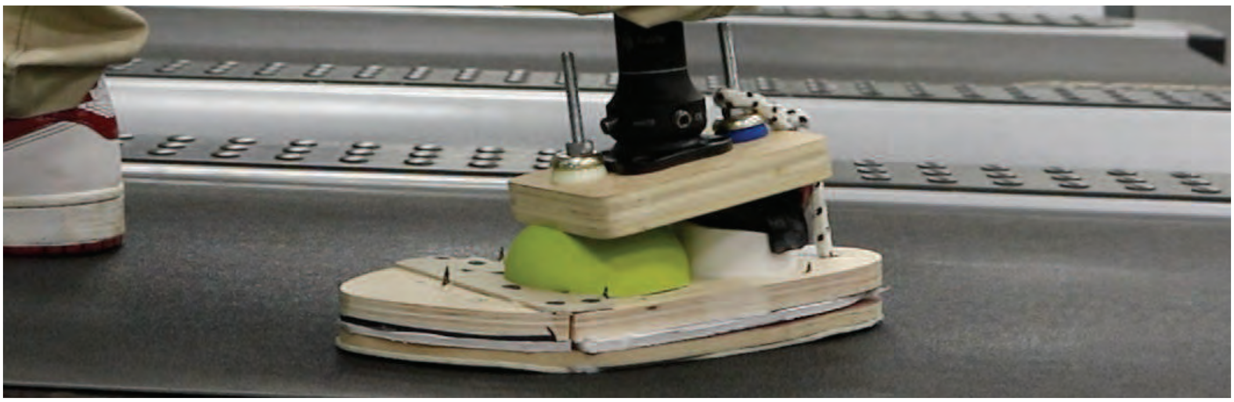
We wanted to reintroduce the ball and socket concept one last time, so we combined the first concept with the sixth to add more controlled rotation.





1. Plantar and dorsiflexion appeared OK, but over time a slight limp appeared

2. Weak abduction, but strong adduction

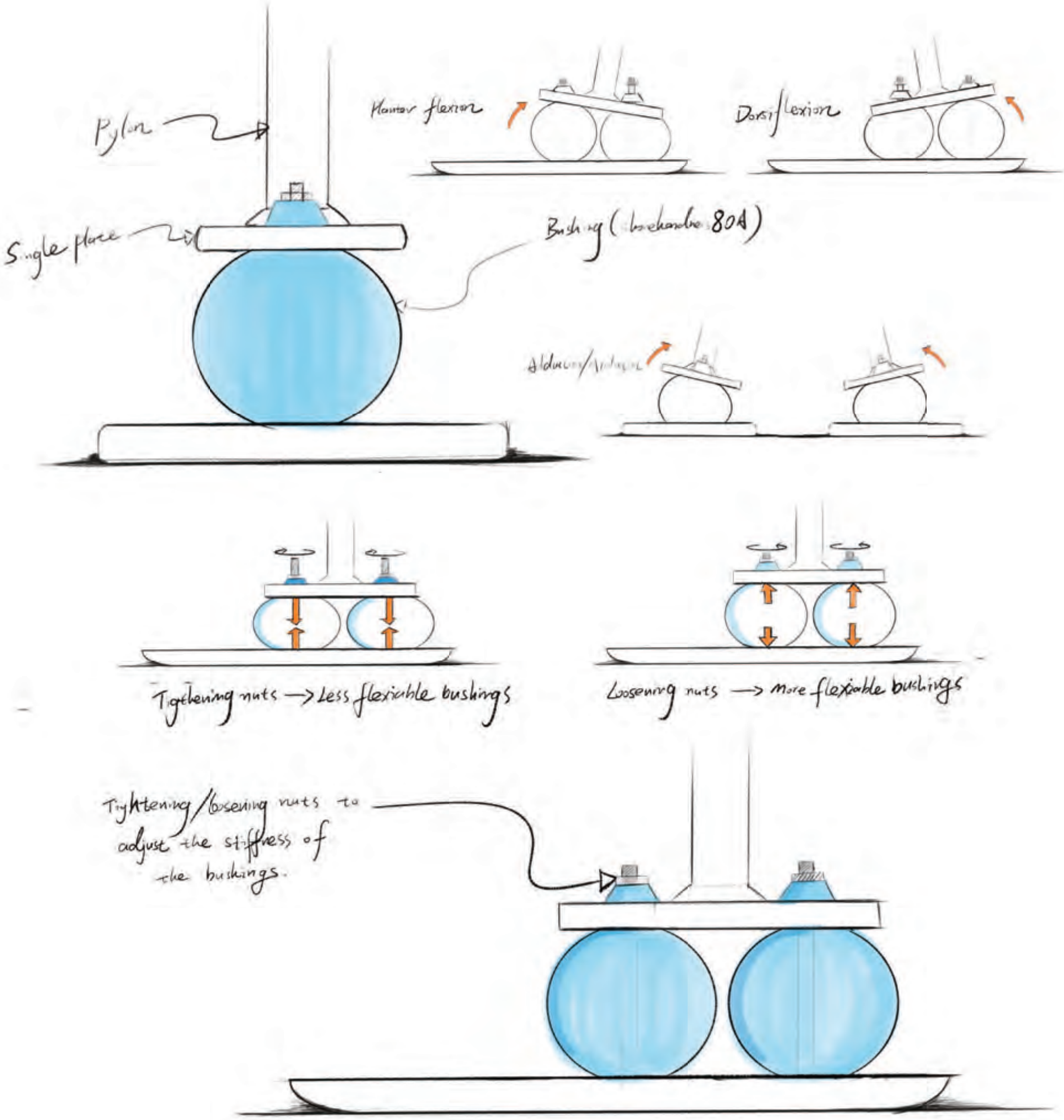


While the movement on this model felt comfortable in the empathy model, testing with Lance showed a different story. The angled top was **significantly throwing off his balance and it didn't feel natural**.

MECHANISM 9

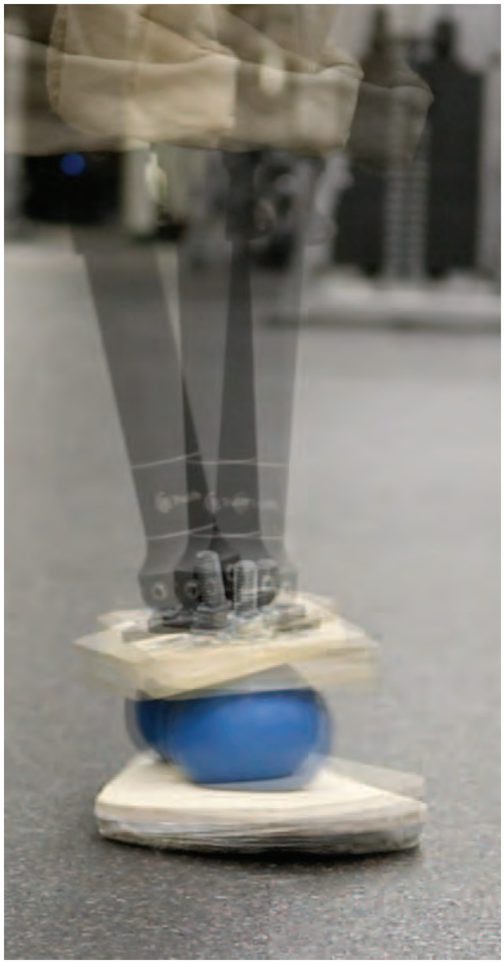
Dual Axis Ball "Bushing" with 80A Topper

An evolution from seven this version utilizes double balls to add more shock absorption. Additionally when tightening down, the balls flatten out at the top. We would later expand upon this.



1. Comfortable plantar and dorsiflexion

2. Clear location of point of flexion

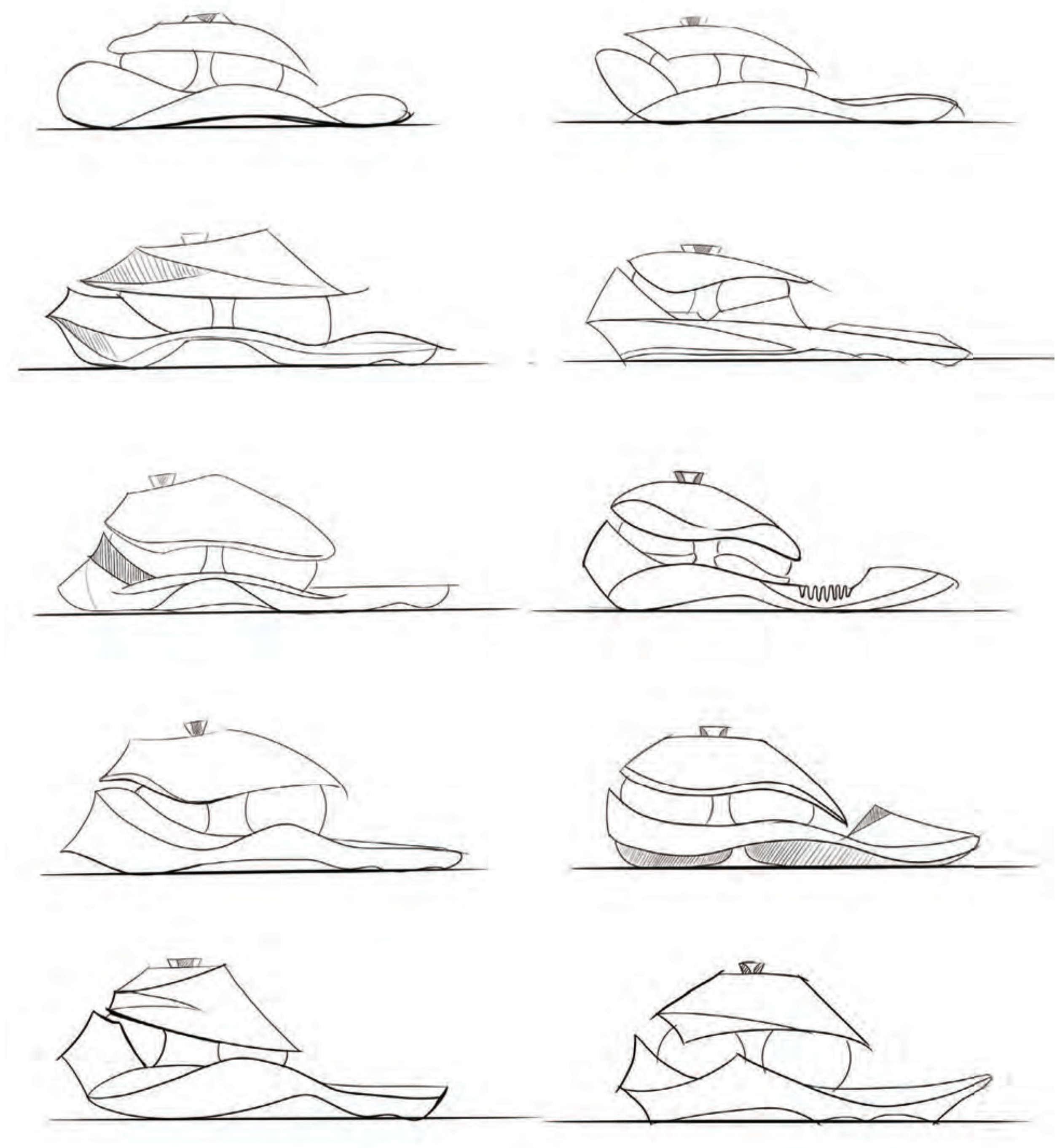


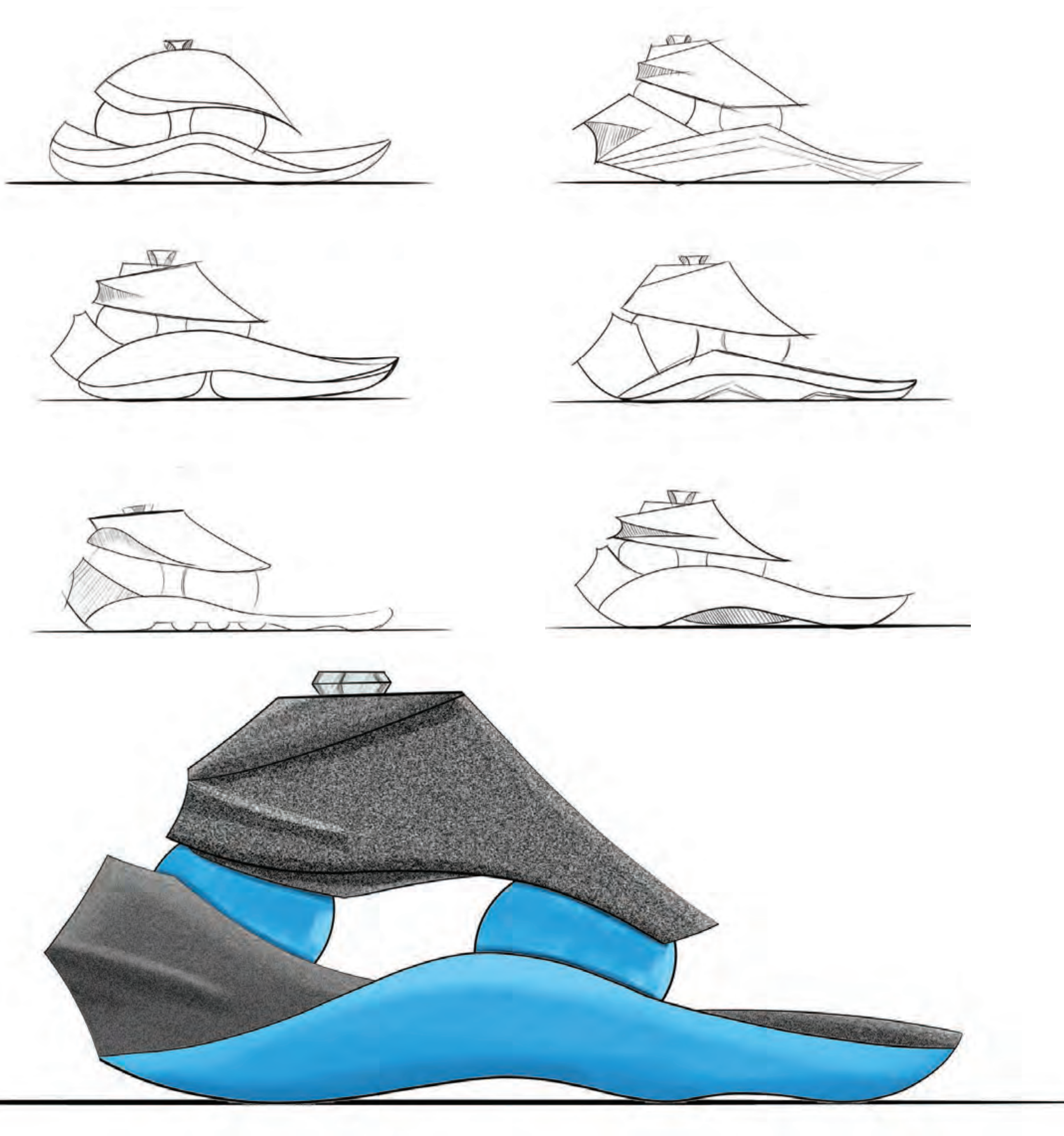
3. Large range of motion for abduction and adduction

Lance felt that the model was safe enough to test on the balance board so with some assistance he attempted to balance. Examination of the footage proved our concept, showing **strong and stable movements in the side to side direction.**

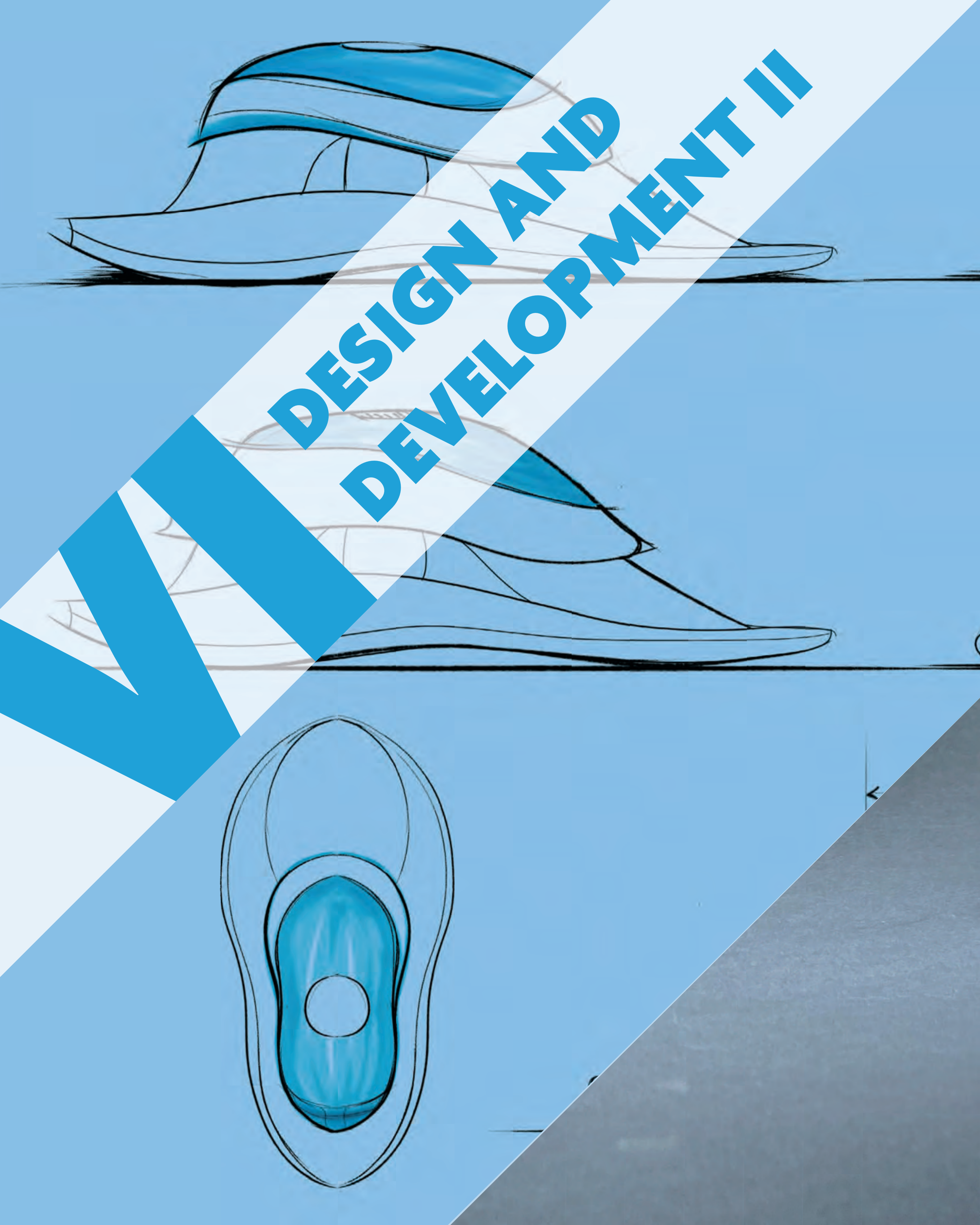
EXPLORING FORM

Confirmation that the **double ball mechanism** worked allowed us to explore some early iterations regarding form. We knew we wanted the appearance to feel familiar, like a shoe, but also feel unique and unlike existing prosthetics.





VI DESIGN AND DEVELOPMENT II

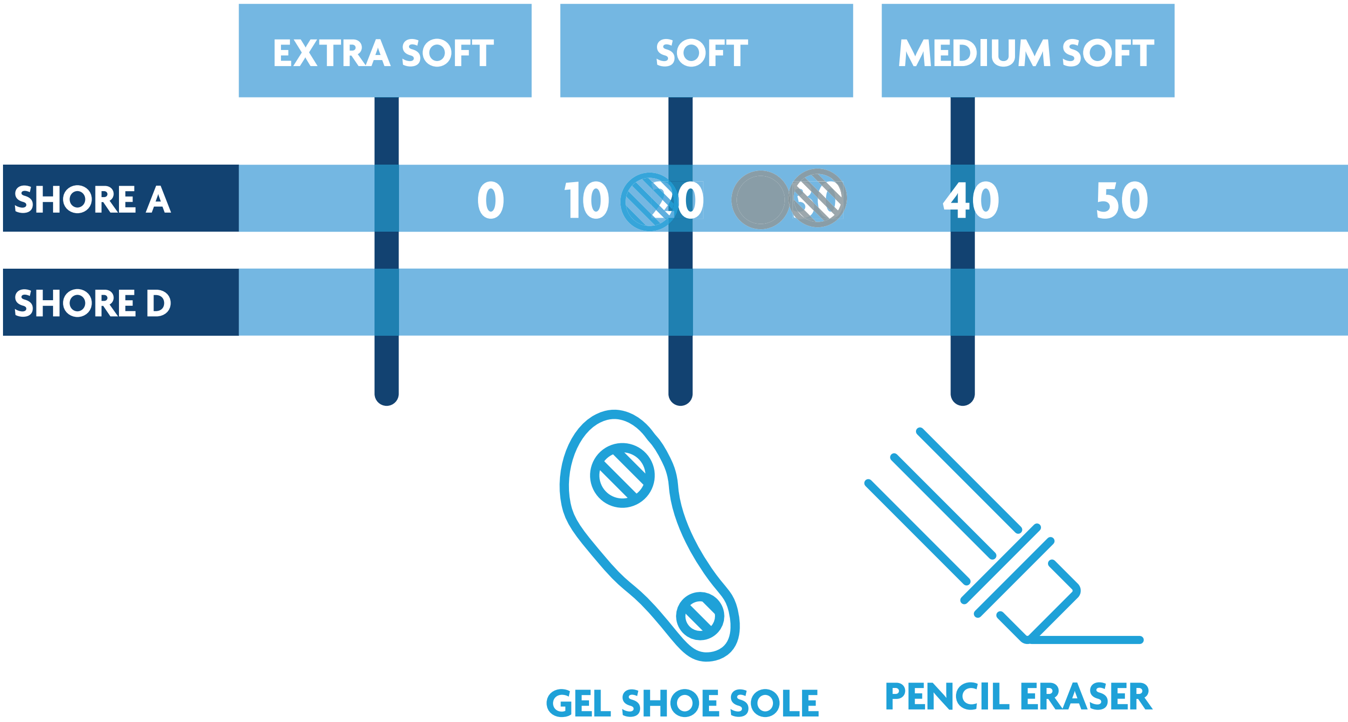


MOVING FORWARD

After a solid testing session with Lance, we were able to push development forward integrating both function and form. After several iterations, we finished with a water proof prototype ready for surfers to test.

UNDERSTANDING THE
SHORE HARDNESS SCALE

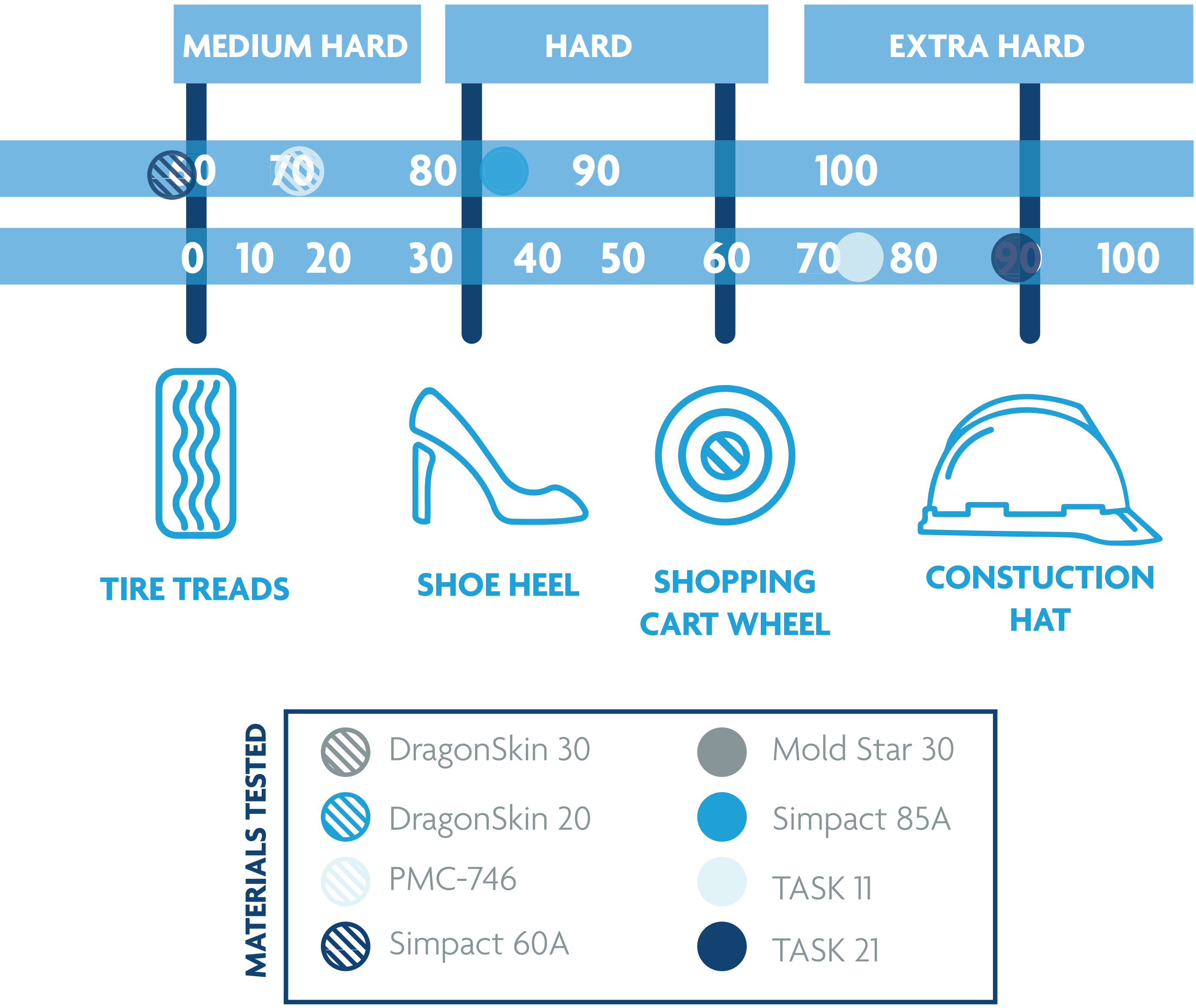
We began to explore a variety of materials we thought exhibited the correct properties we were looking for. Many of these materials were either rubbers or polyurethanes and use a scale called the shore hardness scale to describe how easily the material can deform.



Our initial research told us that the sole needed to provide grip but also have the ability to **bend and flex.** We requested a series of samples from Smooth-On and visited their store to further investigate our options.

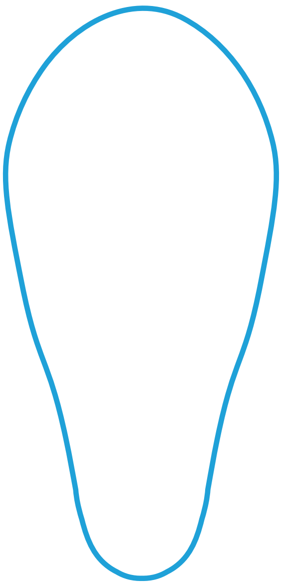
DISCOVERING THE PERFECT STIFFNESS

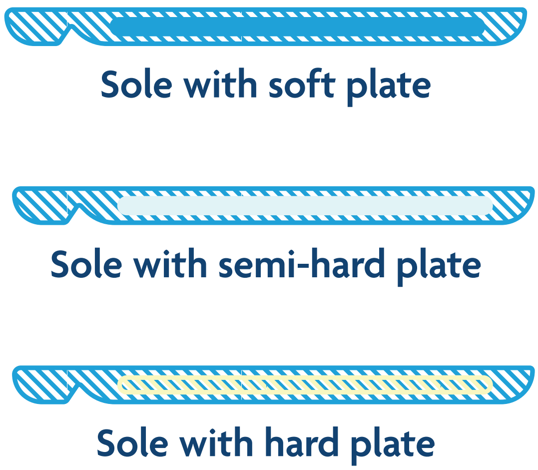
We ended up **testing 8 different rubbers and urethanes** before settling on our final materials. Some were too soft, while others were too brittle. Below are the durometers we tested. The chart will be **referenced throughout the next section.**



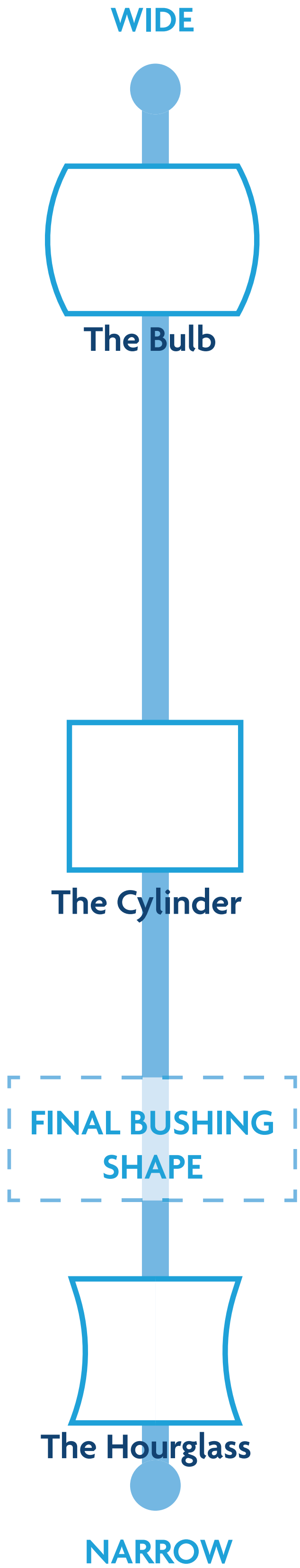
THE BULB AND THE HOURGLASS

Once we decided on the double axis bushing we wanted to test a range of shapes. We created a scale and forms on either extreme end of the scale. This allowed us to nail down exactly how much movement we would need.





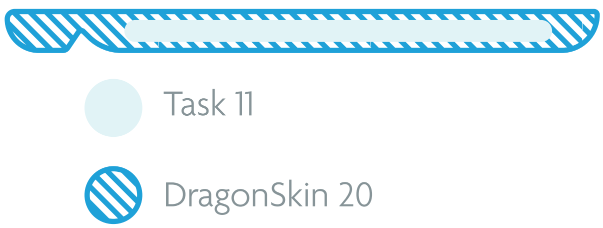
These three bushings were then tested with three initial soles. These first soles all used the same mold and we experimented with **various materials of different hardness.**



SOLE MATERIAL RESEARCH

Sol

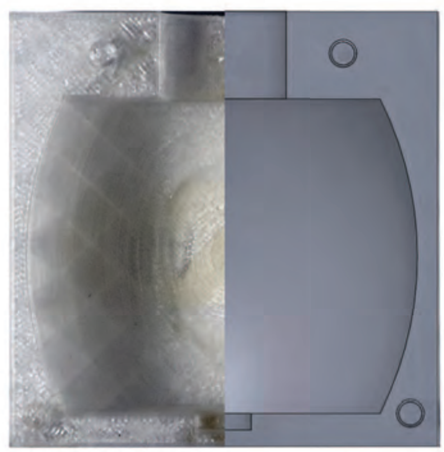
Sol



Sol

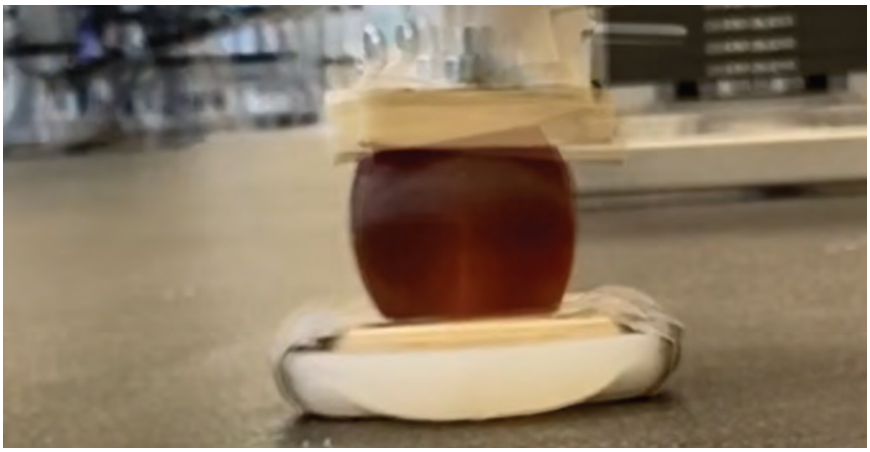
THE BULB

On the one extreme of the scale, we wanted to test a shape that was similar to the balls, but had a flat top with more curvature. The bulb was the result. The top extrusion allowed for continued motion, even when the wood was placed on top.



Mold for "The Bulb"

"The Bulb" cast from PMC-746



Abduction and adduction test with "The Bulb".

➕ 1. Large surface area on top created a secure fit

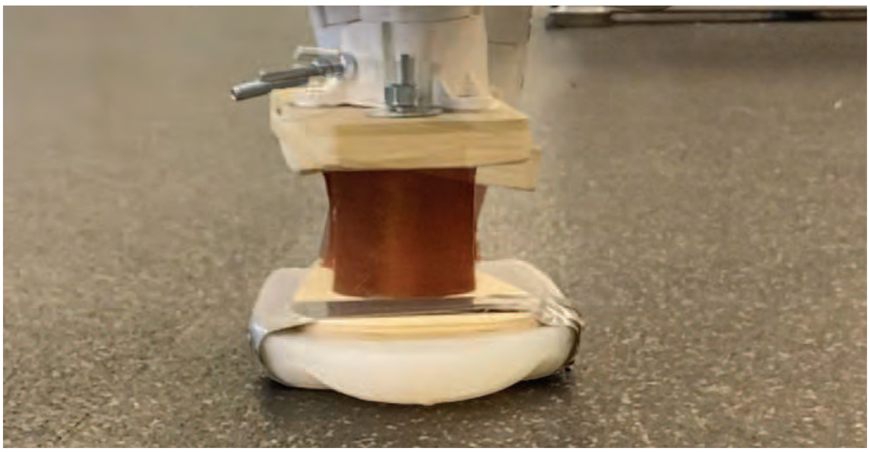
➖ 1. Large shape limited side to side motion

THE CYLINDER

In the middle was the cylinder. Doing this allowed us to examine what about the shape was helping (or hurting) the flexing. This neutral player proved to us that thinner was better. It also helped validate the top extrusion.

Mold for "The Cylinder"

"The Cylinder" cast from PMC-746



Abduction and adduction test with "The Cylinder".

+ 1. Large surface area on top created a secure fit

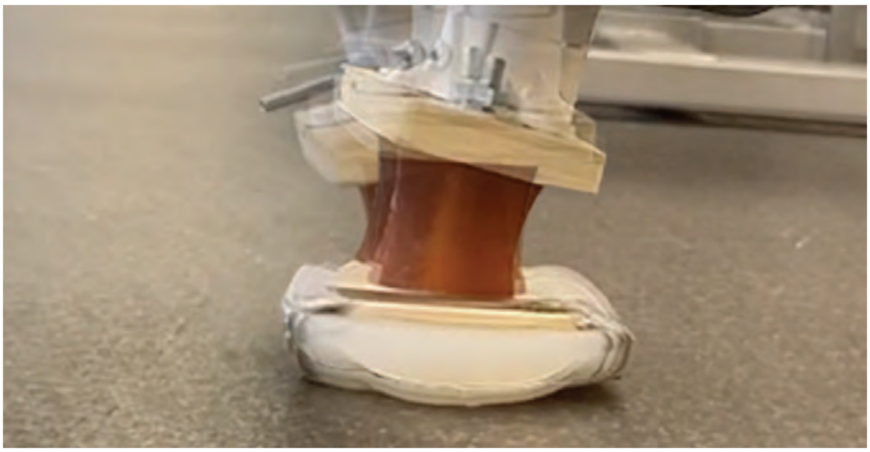
− 1. Flexed okay but the straight walls still limited movement

THE HOURGLASS

The hourglass represented the extreme end on the other side of the scale. While it added to the form it also encouraged flexing in either direction. We got extreme angles from this, but determined it could be controlled.

Mold for "The Hourglass"

"The Hourglass" cast from PMC-746



Abduction and adduction test with "The Hourglass".

+ 1. Curved edges encouraged flexing to the sides 2. Flat top created secure mounting and fit	− 1. Thin middle profile created lots of flex but could easily be adjusted

ADDING MORE RIGIDITY

Half way through the testing we determined that the exterior material for the sole was too soft and was negatively effecting the results of the bushings. Primarily it was causing bending in the foot sooner than it should. We solved this by adding a thing piece of wood that could add rigidity but still flex.

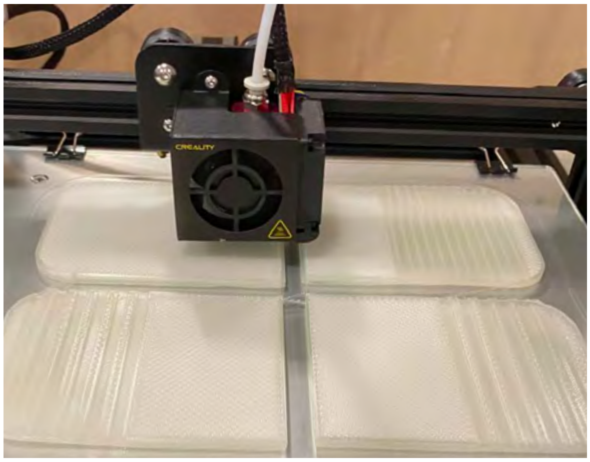
Separation occurring during walking

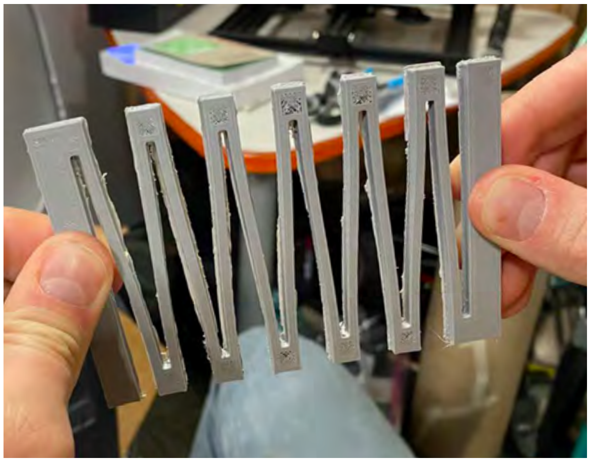
Tape to eliminate flapping that was occurring when walking

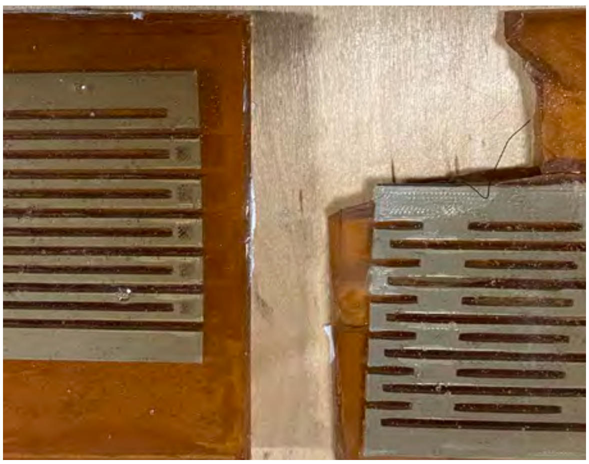
➕ 1. Wooden plate stiffens sole and adds rigidity 2. Edges of the sole help with adduction/abduction	➖ 1. Overall material for the sole is too soft 2. Wood has the potential to split over time

PINPOINTING FLEX WITH LIVING HINGES

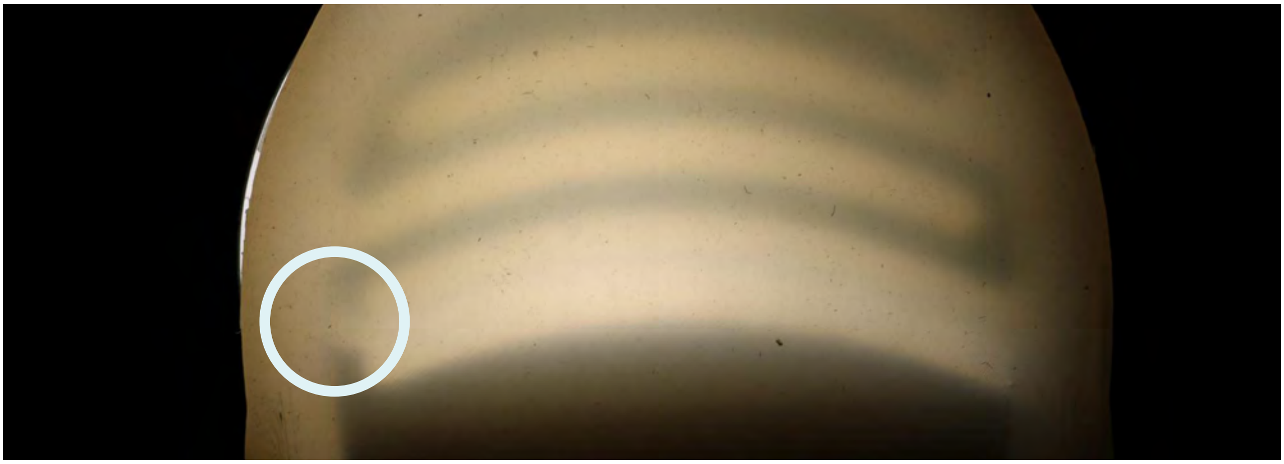
The previous tests, and the need to add the plate of wood told us that we needed a more ridge plate. One idea we had was to place a living hinge at the front of the toe, to add rigidity, but also encourage bending. We started by **encasing two 3D printed living hinges in PMC-746.**







We quickly learned that while the PMC-746 was a **good durometer**, the material itself was **too brittle**, especially when casted thin. We decided to move forward with the living hing experiments, but **change the material it was cast in.**



(Broken) living hinge molded into DragonSkin 20

BREAKING IT DOWN

Our final tests with the living hinges included testing both 3D printed versions and cast versions. Over time the material lost it's ability to flex back to the "home" position, making it unreliable. Ultimately it caused the material to snap.

Locating stress point

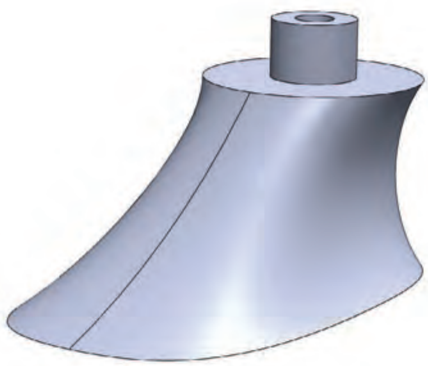
Final living hinge model, 3D print ultimately used to test stress (Permanent flex up can be seen).

Broken toe in the cast Task 21 model

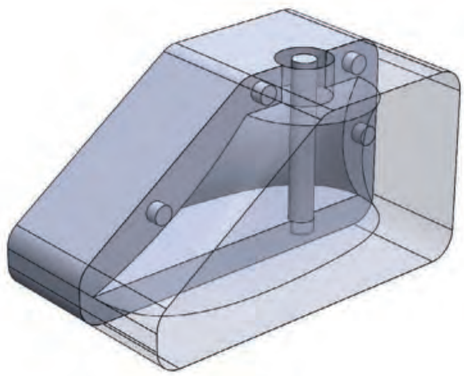
DEVELOPING THE FRONT BUSHING

To develop the next round of bushings we made some rough models in Rhino to explore the form. We took into consideration the hourglass form and sculpted several variations, finally landing on the scooped version.

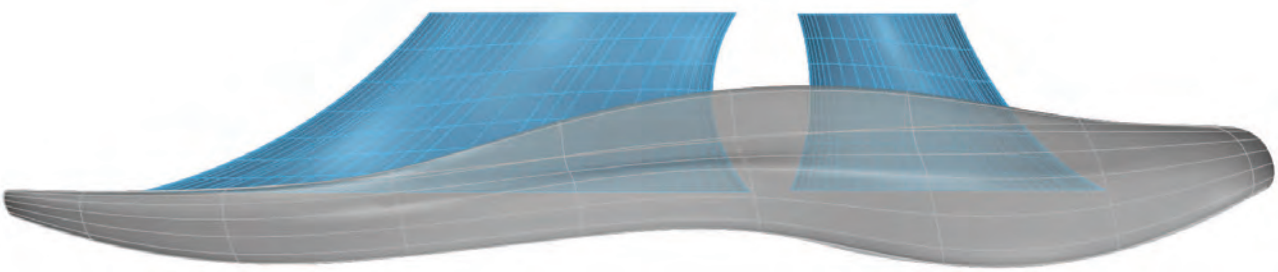
Exploring form in Rhino



Created the front in Solidworks



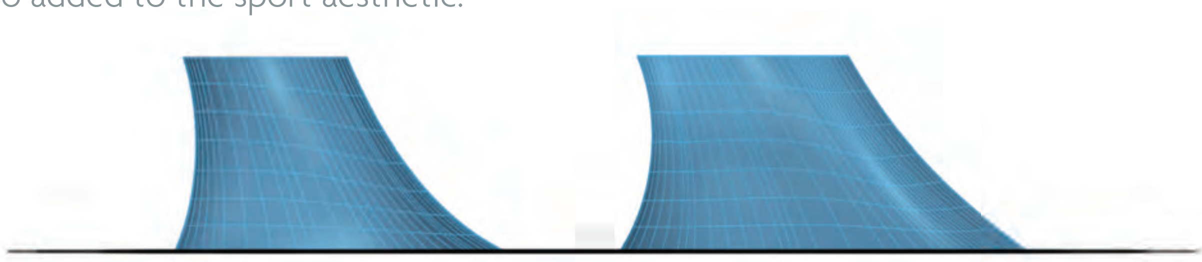
Bushing molded from Simpact 60A



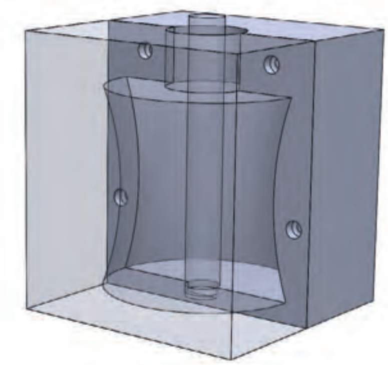
Further experimenting bushings with the sole in Rhino

RETHINKING THE BACK BUSHING

Since the back bushing was going to serve a slightly different function than the front bushing, the form could be different. While it still needed to flex, it was going to also be absorbing shock. The different forms also added to the sport aesthetic.

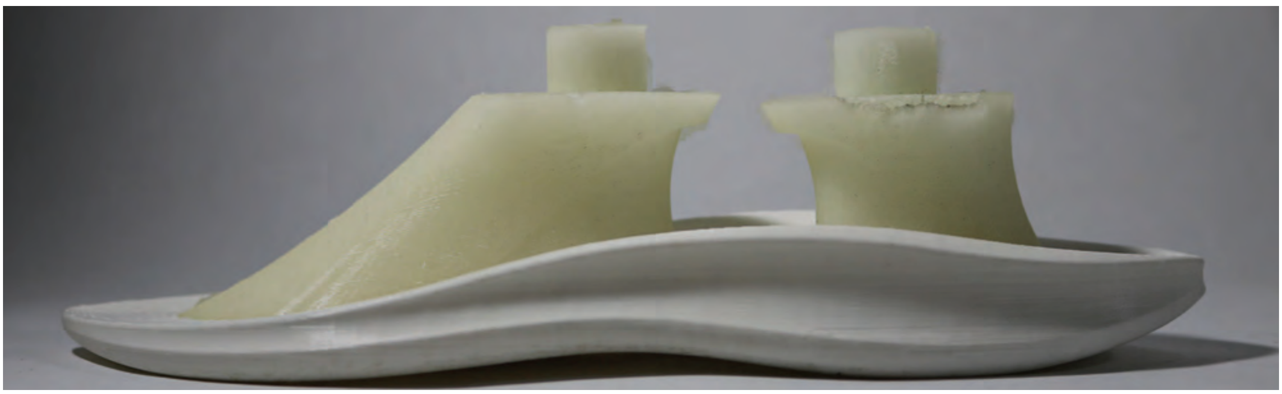


Exploring form in Rhino



Bushing molded from Simpact 60A

Created the part back in Solidworks



Cast bushings (Simpact 60A) in with 3D printed sole

PUTTING FORM TO THE TEST

We put the bushings to the test by testing them with the sole that included the 3D print. This allowed us to determine that the print was not preforming well and that the bushings needed to be attached to the sole.

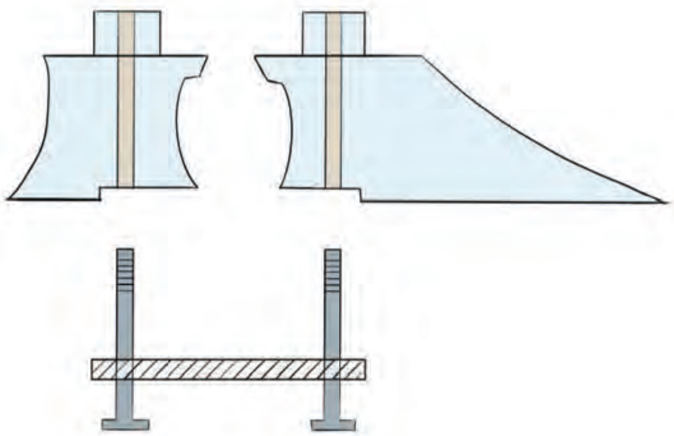
Using our empathy model to test the new cast bushings: flexing of the sole

+ 1. Increased support and flex while walking 2. Shock absorption could be felt universally	− 1. Detached bushings created a “slapping effect” 2. Separation also cause sole to “warp”

Separation observed while walking

TOGETHER IS BETTER

Our previous tests identified the stress point, so with this information we were able to place a plate where rigidity was needed (under the bushings) , and enhance flexibility where it was required (front of the foot).

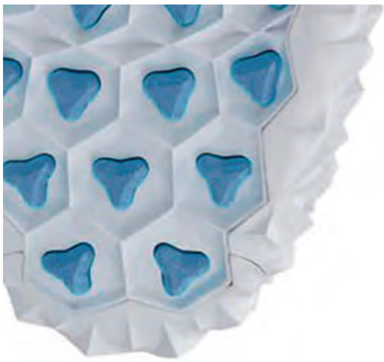


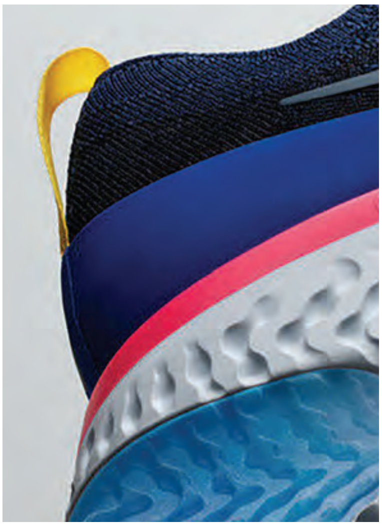
Modified bushings to test rigid plate (1/8")

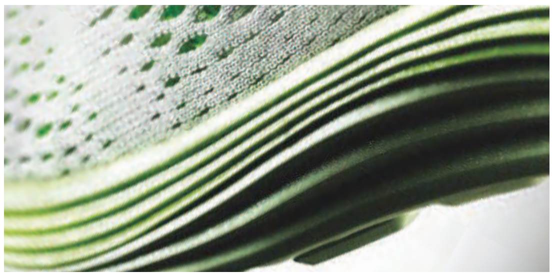
Taping the bushings to the sole created a much stronger and natural feeling when walking

DRAWING INSPIRATION

The form of the foot was going to heavily rely on the design of the sole. We drew inspiration from existing shoe products as well as forms in nature such as the flow of the ocean.



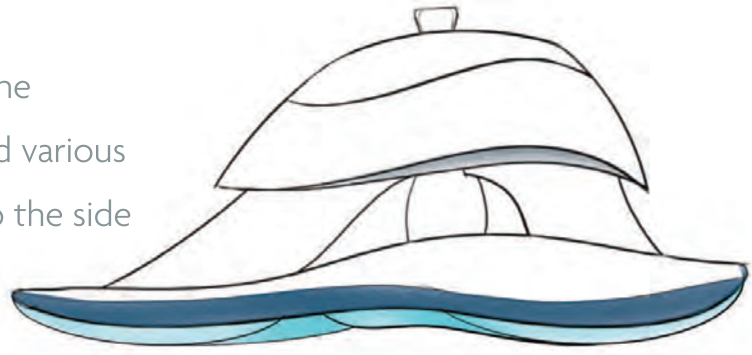


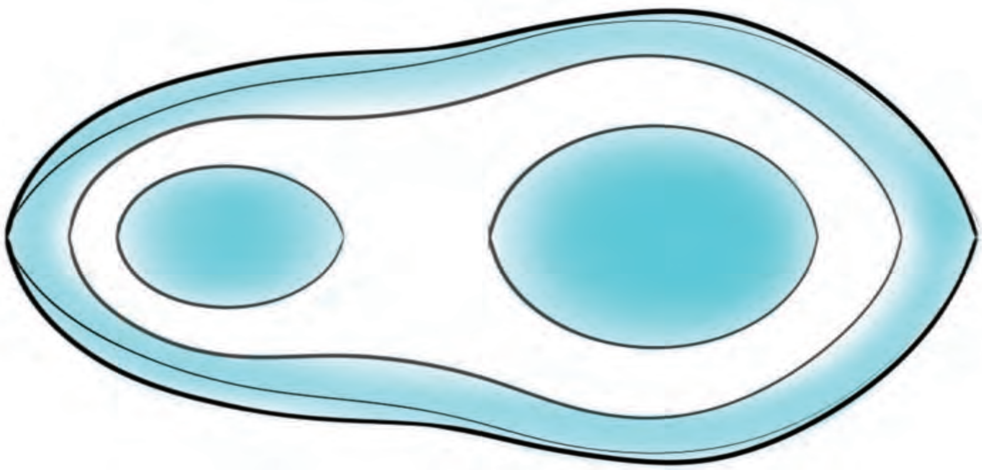


Since the foot would be used at the beach we aimed to create a form that embraced the culture of surfing. Smooth edges, with deep shadows evoking the feeling of tranquility was our goal.

MAXIMIZING GRIP WITH TREADS

Consideration also went into how the treads would appear. We considered various aspects including wrapping them up the side of the foot to maximize the grip.

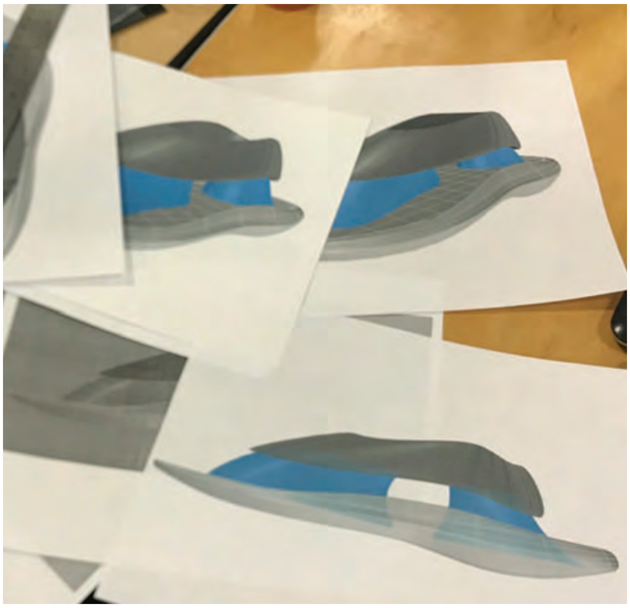




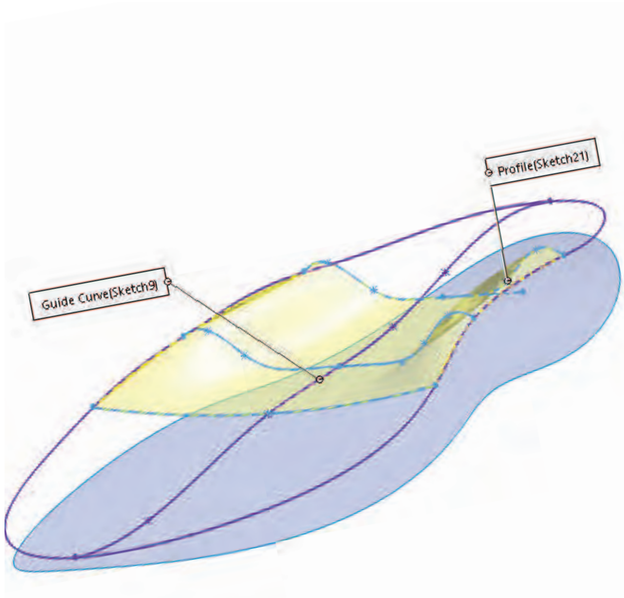
We settled on a simple dual-circle design, for Round One, to make casting simpler.

SURFACING THE SOLE

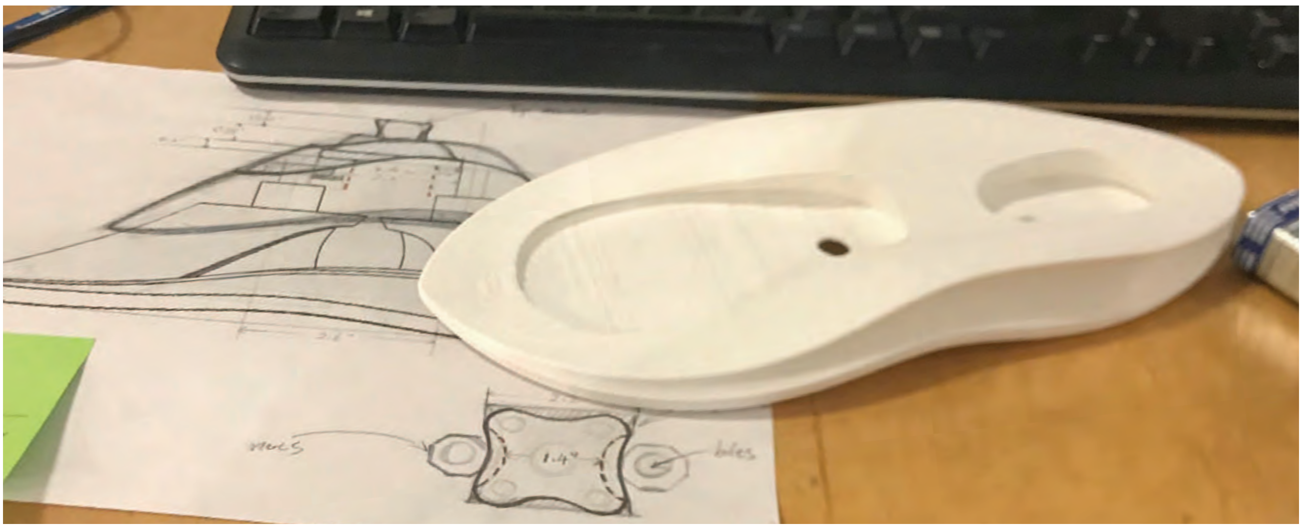
While Rhino allowed us to quickly explore forms, it wasn't ideal to build the models that we would be casting. We transitioned to Solidworks, which gave us more control over the aspects of the design we would have to repeatedly edit.



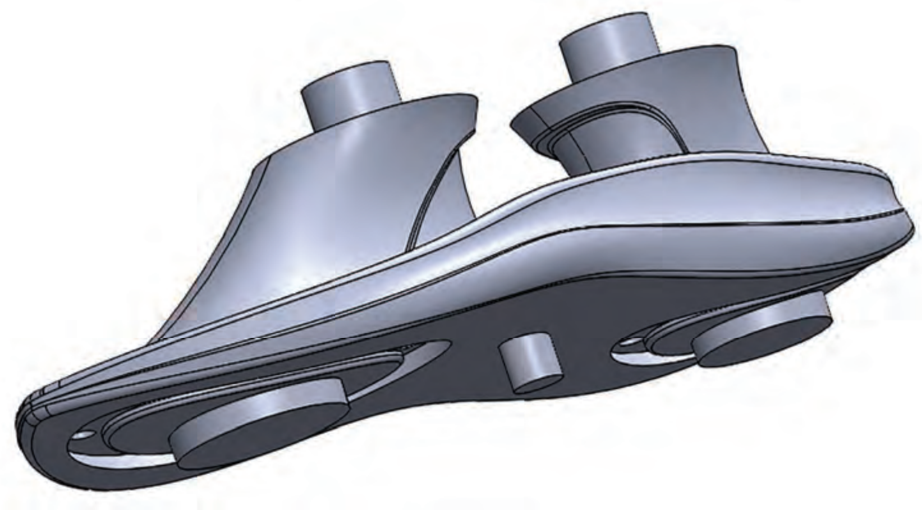
Referencing Rhino Model



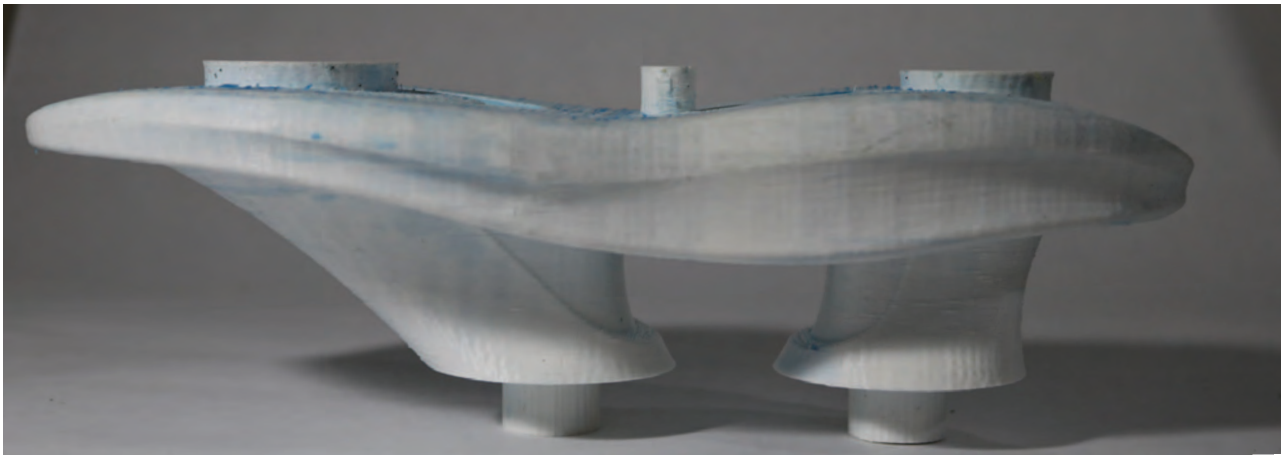
Sketching out surfaces



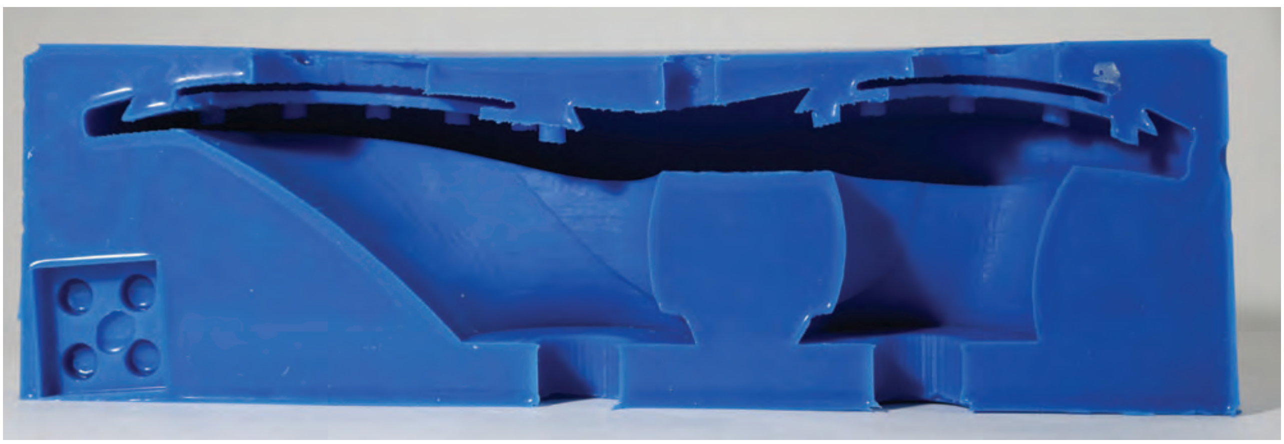
Preliminary model ready for mold design



Designing the mold positive in Solidworks



3D printed Mold positive



Mold made from 3D Printed positive and MoldStar 30

TESTING WITH LANCE
TRIP TWO

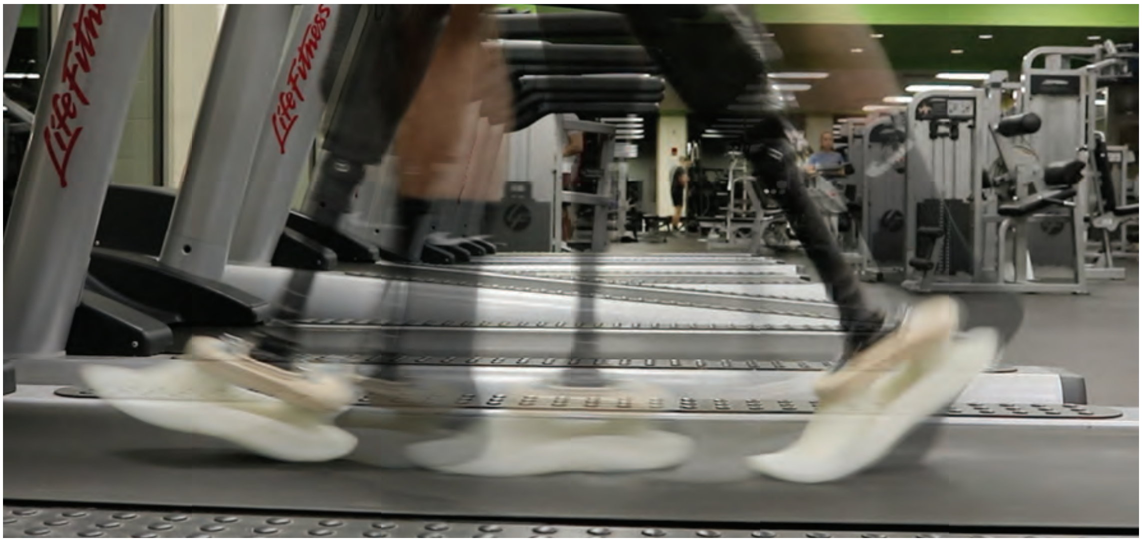
It was crucial for us to validate the aspects we had been focusing on with our empathy model when went to test with Lance for a second time. The four key aspects we needed to test was the ability to pop-up, the abduction, adduction, plantar and dorsiflexion of the model. We also needed to test our first round of grips. The goal was to discover what needed to be changed for our surfable test model.

As we prepped for our California surf trip, we needed to test our current model and locate any large issues.

PLANTAR AND DORSIFLEXION

THE TREADMILL

We continued our previous testing methods to examine the motion in the new model. The treadmill continually proved to be helpful in revealing problems with our device when walking.



+	−
1. Motion looked very natural 2. Material absorbed shock after each step	1. The front felt a little short which we determined was due to the material thickness in the front

THE POP-UP
EXAMINING MOTION AND FLEX

To test the pop-up we had Lance simulate swimming out in the hallway. Since he is new to surfing with one leg he practiced a few times, before feeling comfortable. He felt that the foot reacted similar to his existing one.

+	−
1. Shock from landing was absorbed by the material 2. Edges of sole flexed making landing easier	1. Tip of the foot would slip 2. Grip wasn't spread out enough on the bottom

ADDUCTION AND ABDUCTION
THE BALANCE BOARD

In order for us to best understand how the foot was reacting to Lance's movements, we had to get close to examine it. While the treadmill was good for showing plantar and dorsiflexion, no such test existed for the other (most important) direction. This led us to mount a GoPro to our balance board, creating a unique and informative point of view.

GoPro balance board rig

In addition to our balance board tests we had Lance move on the foot in various ways. This included getting on his toes and moving left to right. Our goal was to push the foot to its max capacity and locate any pain points.

1. Responded well, even with sudden drops
2. Edges flexed for small quick movements
3. Sole encouraged flexing
4. Multi-material helped with gripping to the board

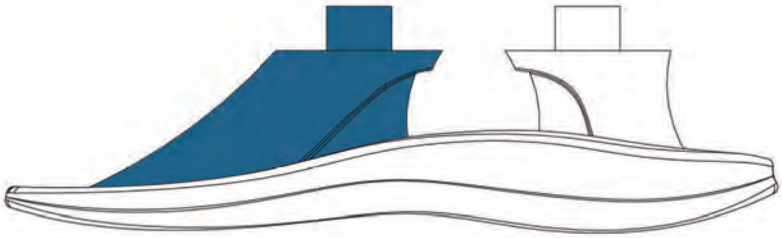
CREATING THE
SURFABLE MODEL

The final model we would create required us to mold several parts separately, and then bring them together for the final casting. We decided for this model to mold the bushings and the sole as one part, to ensure durability when testing in the water. Additionally we had to float the plate that would house the hardware for the dual axis. Planning was done in two stages: First digitally on the computer in Solidworks and then for real. Between cure times one foot took about 10 hours to produce.

This model required extensive planning, forcing us to consider how various parts would be cast together.

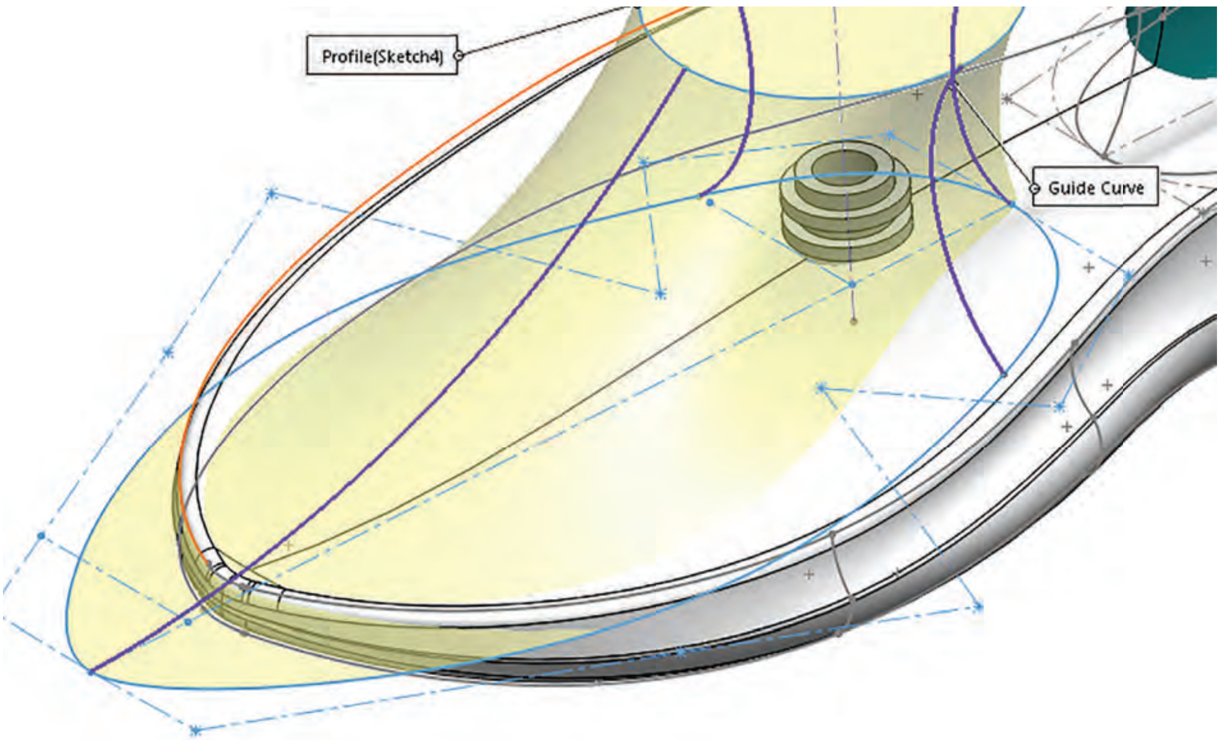
IMPROVEMENTS BASED ON TESTING

Lance's largest piece of advice was that the foot felt short. We measured against his foot and it was the same length. After analyzing the videos we determined that the front was flexing to early. To combat this we extended the bushing forward, adding more material which thickened the toe box, while maintaining the sweeping form.



Model tested on Lance

Shifting bushing forward based on feedback

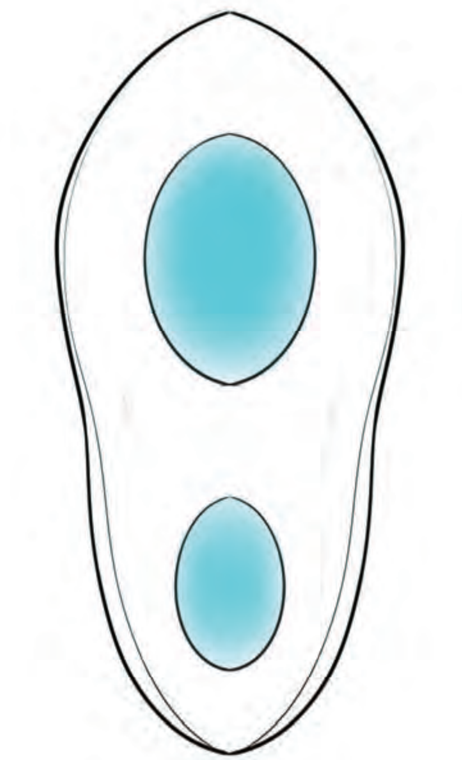


Shifting bushing forward in Solidworks

REVISITING THE TREADS

In addition to our balance board tests we had Lance move on the foot in various ways. This included getting on his toes and moving left to right. Our goal was to push the foot to its max capacity and locate any pain points.

> "The material helped a lot, but it feels a little unbalanced. Try moving the grips to the front and side of the foot."
>
> *-Lance Vargas, Left BK Amputee*



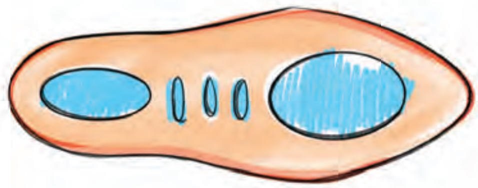
Treads tested with Lance

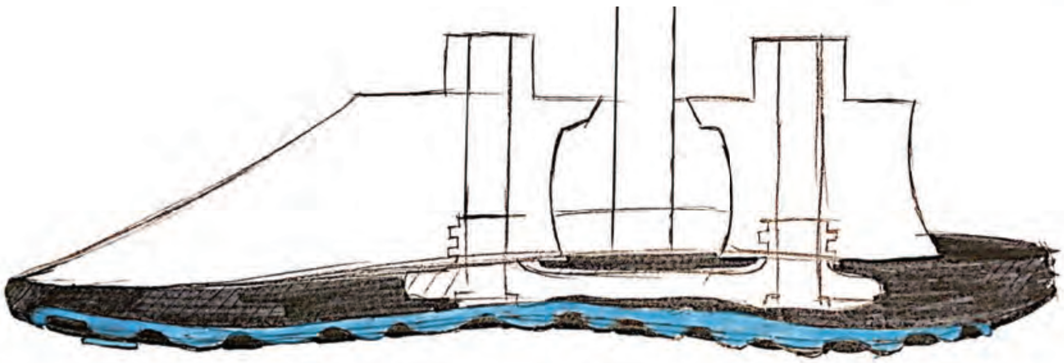
Various sketch iterations exploring grip placement

Final tread design

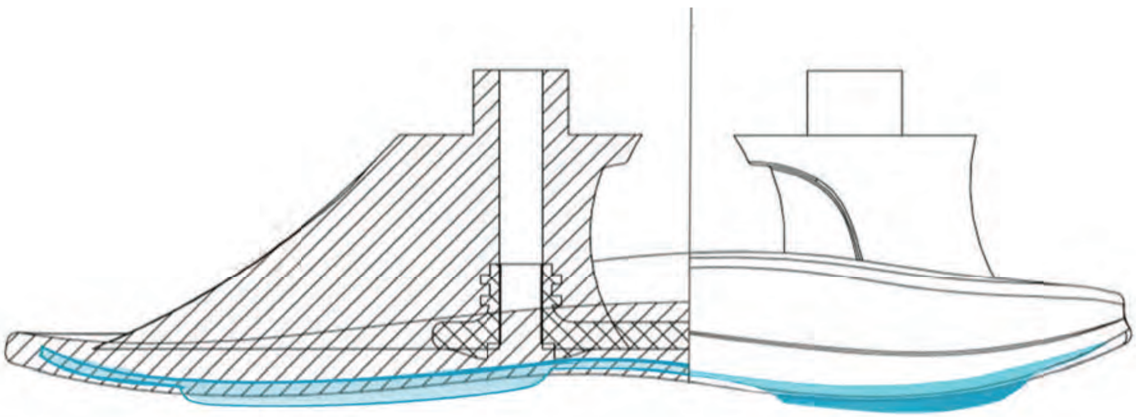
DESIGNING THE INSERT
MOLDED TREADS

Since we needed more surface area for the grips, the challenge of how it was going to be made came into question. Through several iterations, we determined that molding the treads as a separate part and then insert molding it in the final would be the most secure way to proceed.



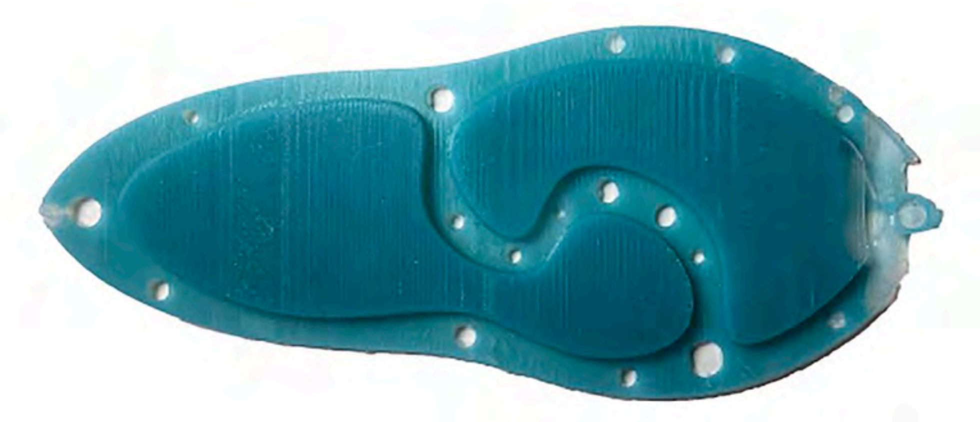


Iteration of how the treads would be insert molded



Modeling out the idea in Solidworks to develop the mold

3D Printed mold for the treads

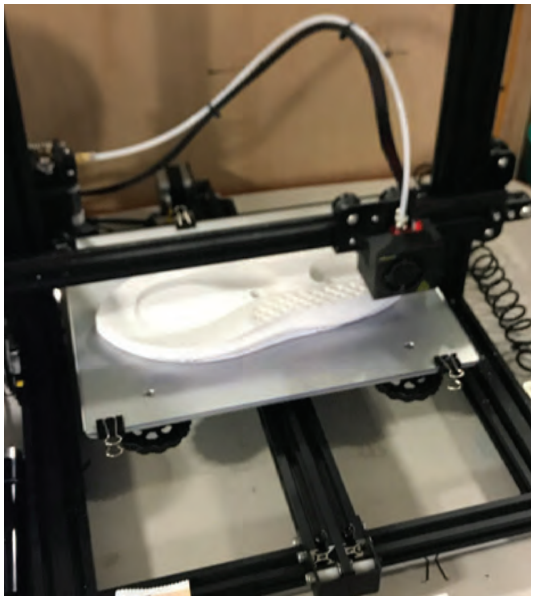


DragonSkin 20 Molded Grips

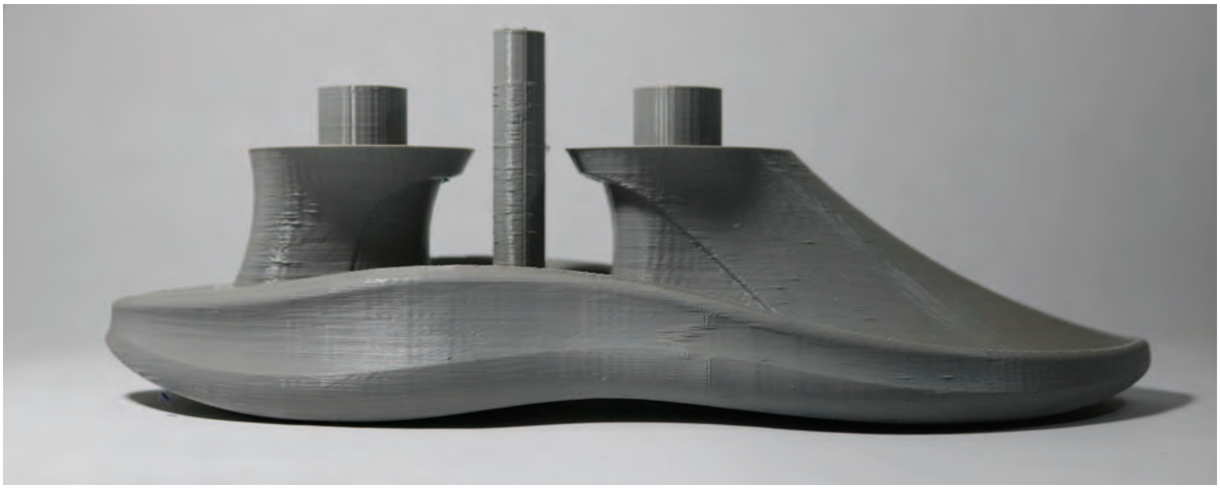
DragonSkin 30 Molded Grips , the final choice

CASTING THE SURFABLE MODEL

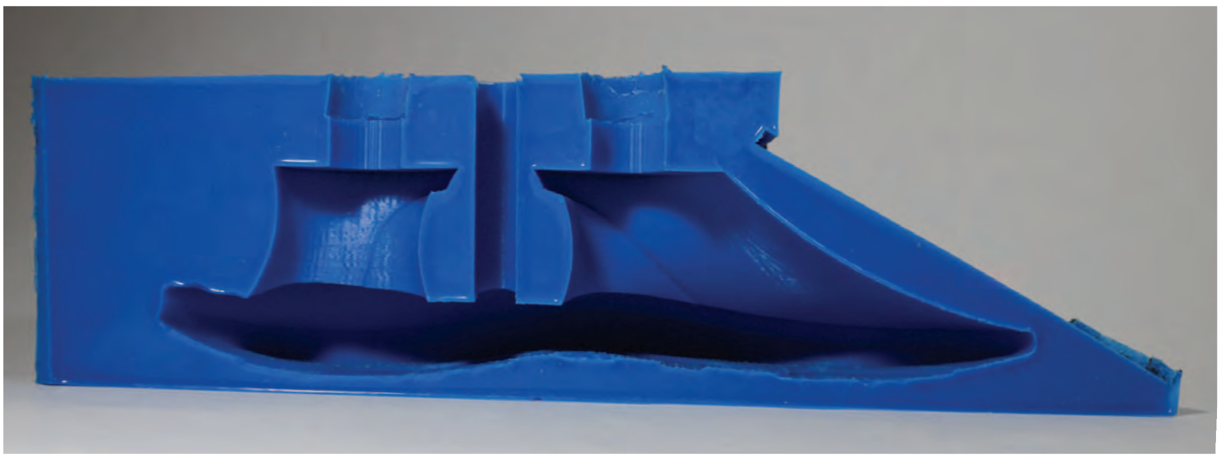
Since the final model had several undercuts, the mold itself needed to be made from a rubber. Additionally previous iterations told us that the **final material, Simpact 60A** heated up during the casting process, causing 3D printed molds to melt. This also allowed us to finish the 3D print, to create smooth surfaces, with no layer marks.



3D Printing the positive



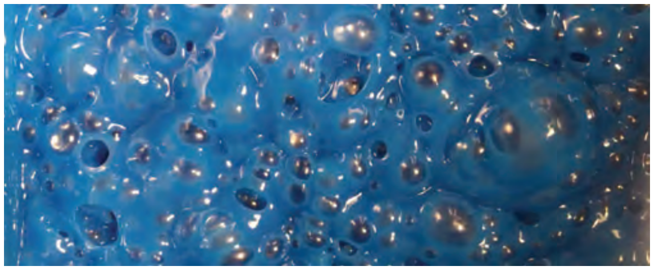
3D Printed Mold Positive



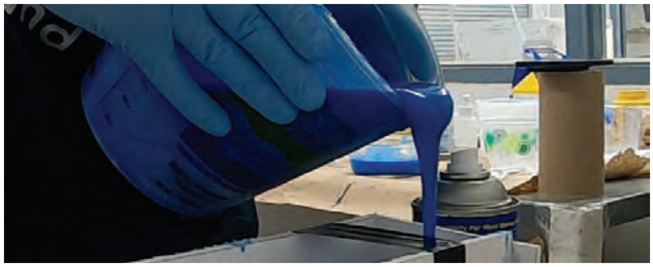
MoldStar 30 Mold, made from the 3D print

THE FINAL POUR

The final pour required us to float both our interior plate as well the treads in the mold. We achieved this by creating locating features in the mold, so when closed up, everything would line up.

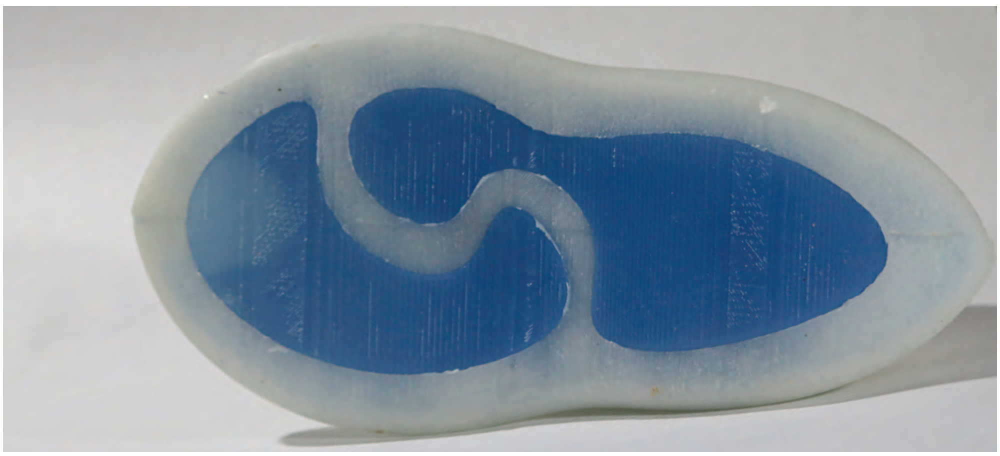


Degassing in vacuum chamber



Pouring the mold

"Stitching" the threads to the mold to ensure no movement



The Final Surfable casting

VIII

TOP SHELL DEVELOPMENT

BRINGING IT TOGETHER

How could our foot stand out from the rest? We wanted Swell to embrace the lifestyle of surfing. Surfing is about freedom. Designing the top shell gave us both a visually aesthetic way to embrace the culture as well as a mechanical one.

DEVELOPING THE TOP SHELL

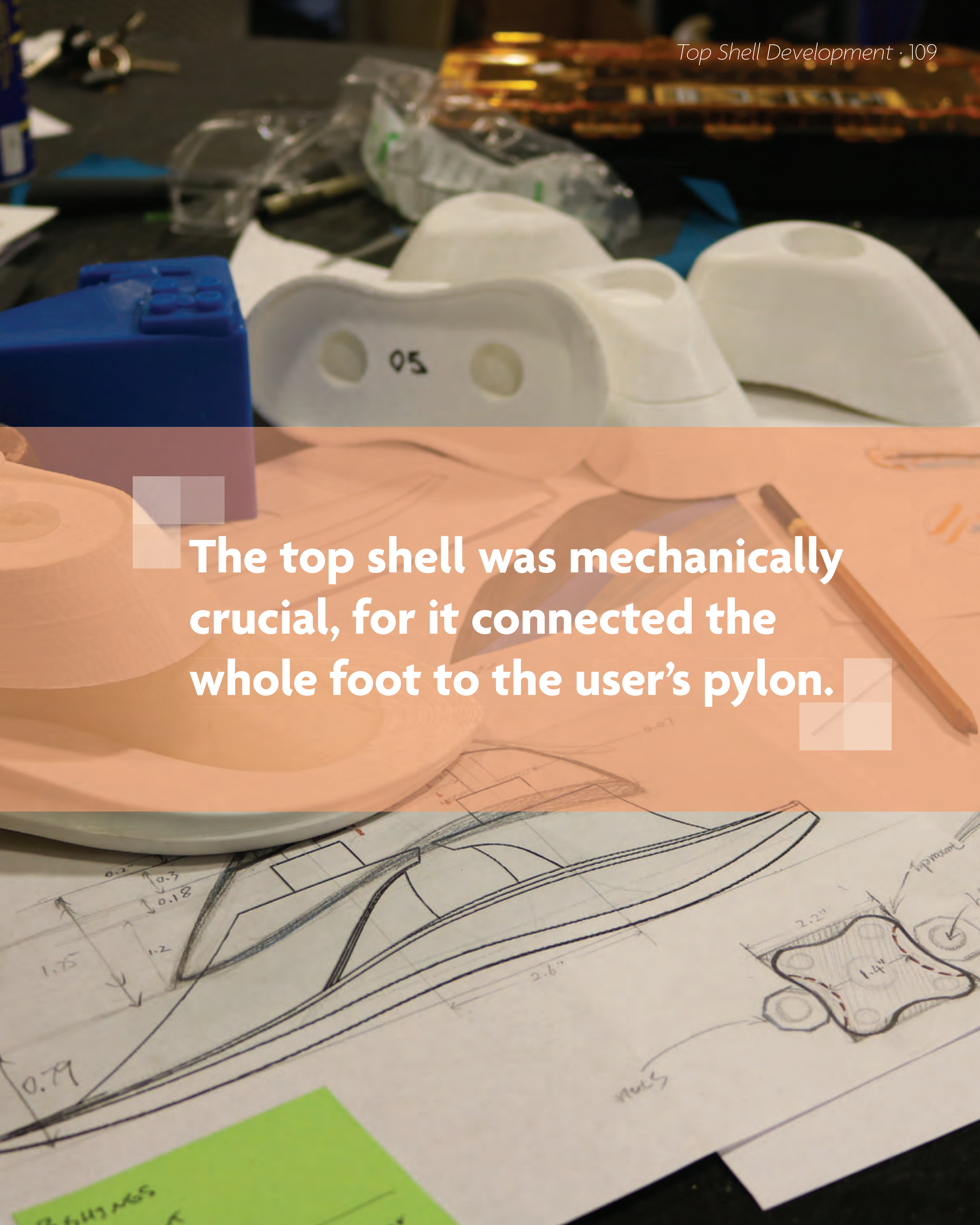
The top piece was crucial in the design. Mechanically, it had to house the pylon adapter securing attachment to the leg. Additionally it was going to house the adjustments for the bushings. Development of the top shell was going on during the same time as the sole and the bushings.

THE BENCHMARKS

COHESIVE FORM LANGUAGE

MANAGE ADJUSTABILITY

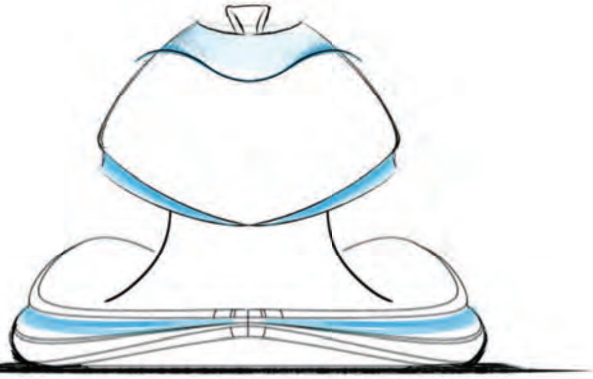
WATERTIGHT SEAL

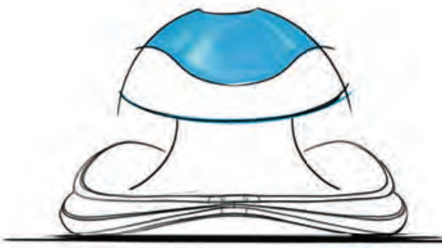


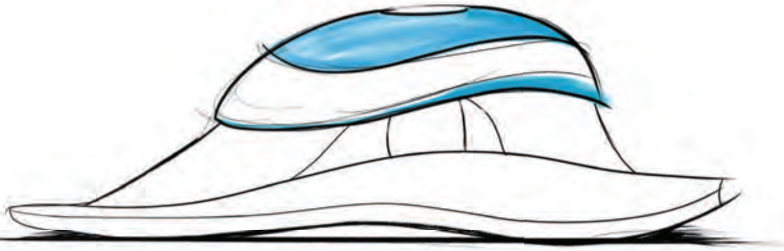
The top shell was mechanically crucial, for it connected the whole foot to the user's pylon.

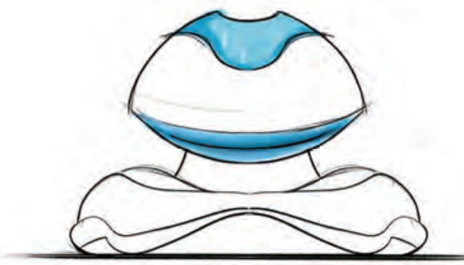
CREATING A COHESIVE FORM LANGUAGE

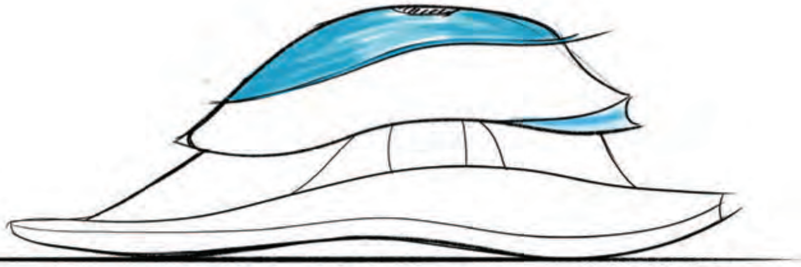
It was important that the form language of the sole matched that of the top, to create a cohesive design language. We wanted the top to have the same type of flow as the bottom sole, but space inside the shell was crucial. We also had to accommodate the size of the male pylon adapter and its dome.

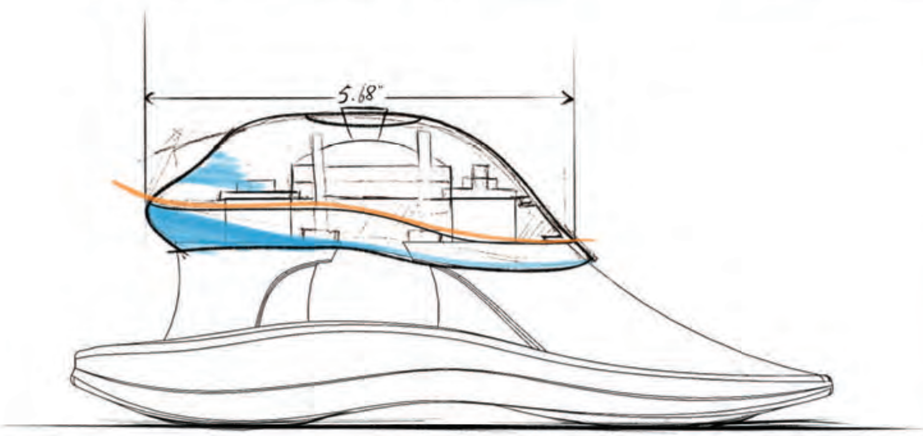


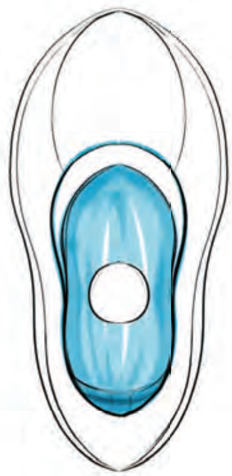


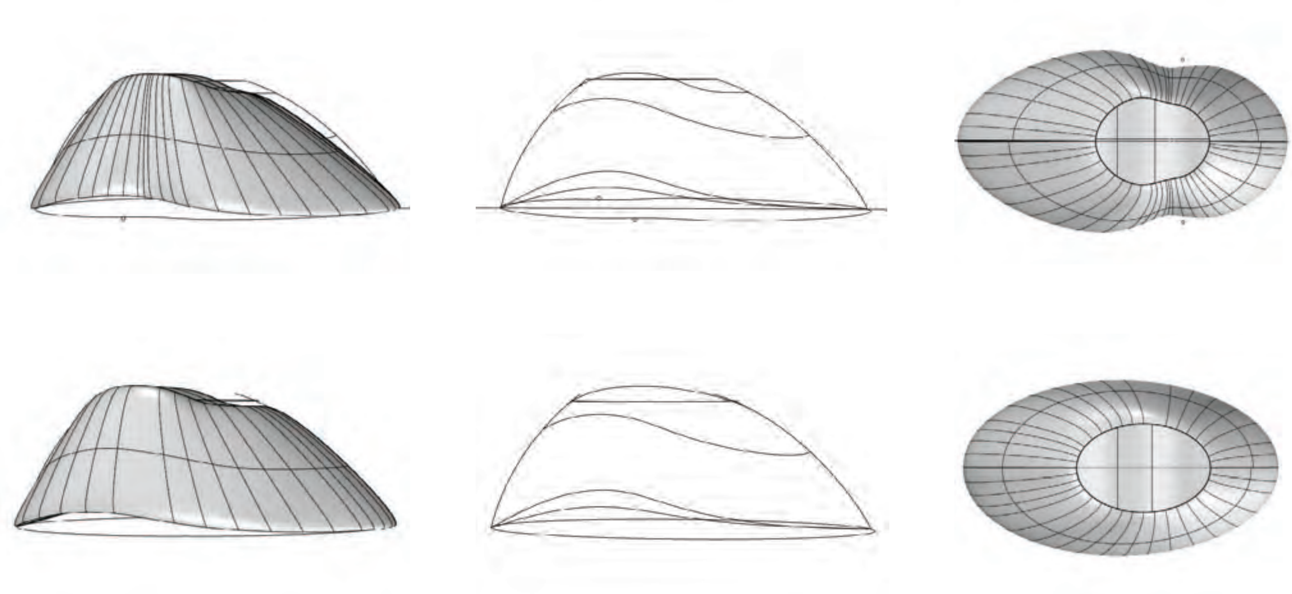












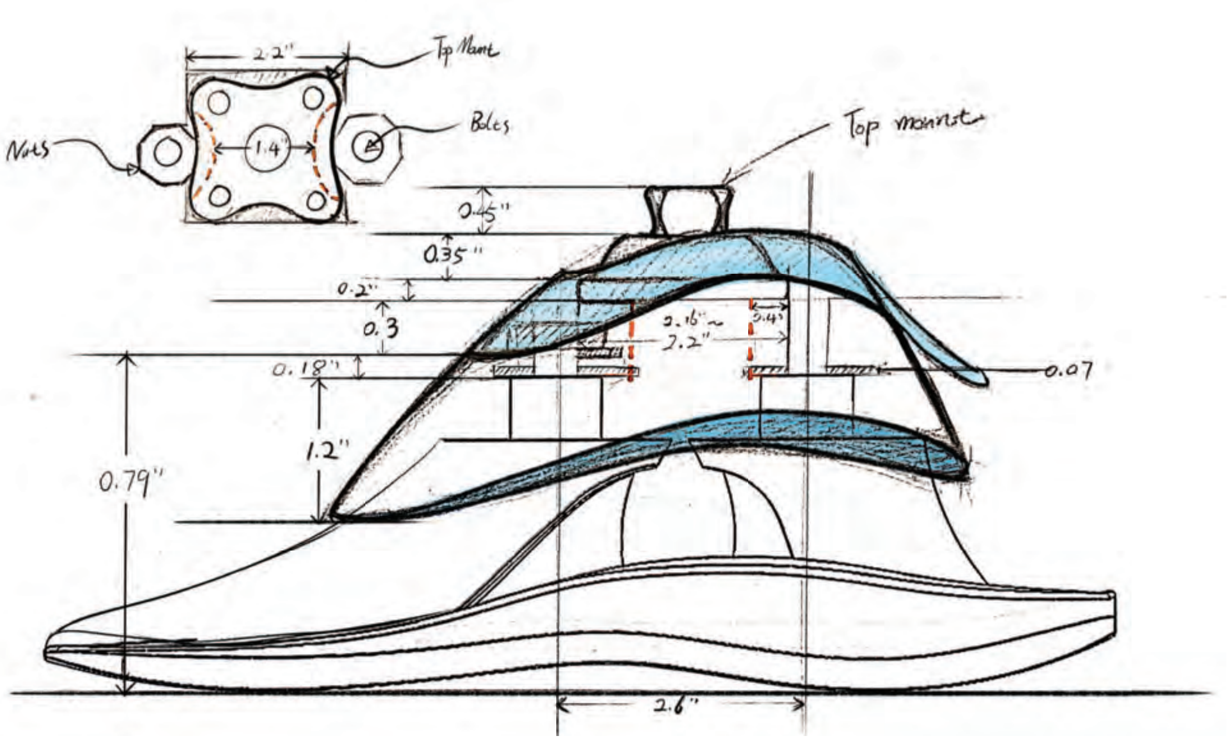
Rhino Exploration

Exploring various forms via 3D prints

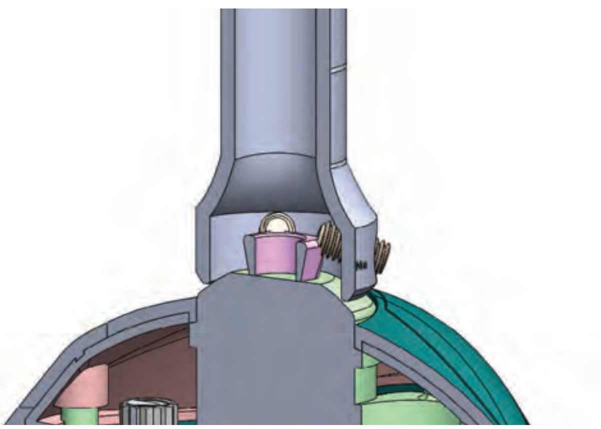
Analyzing Form Cohesion

IRONING OUT THE
TECHNICAL DETAILS

Once we picked a direction for the form, we began to detail out the technical aspects in Solidworks. We did this by overlaying the form and sectioning it, ensuring we had enough space for the details.



Analyzing Form Cohesion

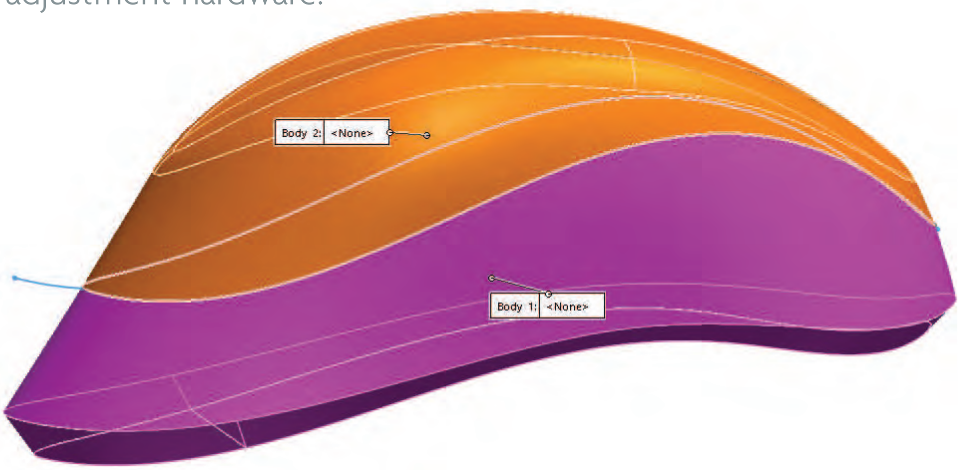


Creating the Pylon column in Solidworks

While we planned to insert mold a pylon adapter in the final model, our test model had to be outfitted with a stock part. We had to alter sections of the design to work with the form.

ENSURING ADJUSTABILITY

When we analyzed the prosthetics on the market, all of them had some form of adjustability. For our device, this was found in the stiffness of the bushings. We integrated a split line into the form, to create an access point to reach the adjustment hardware.

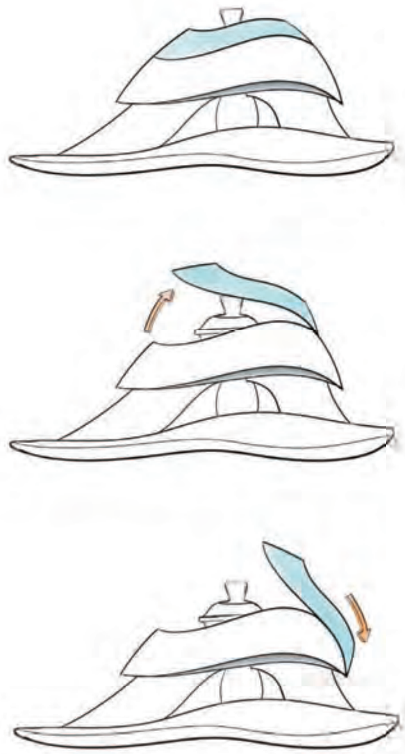


Splitting the top shell into two parts

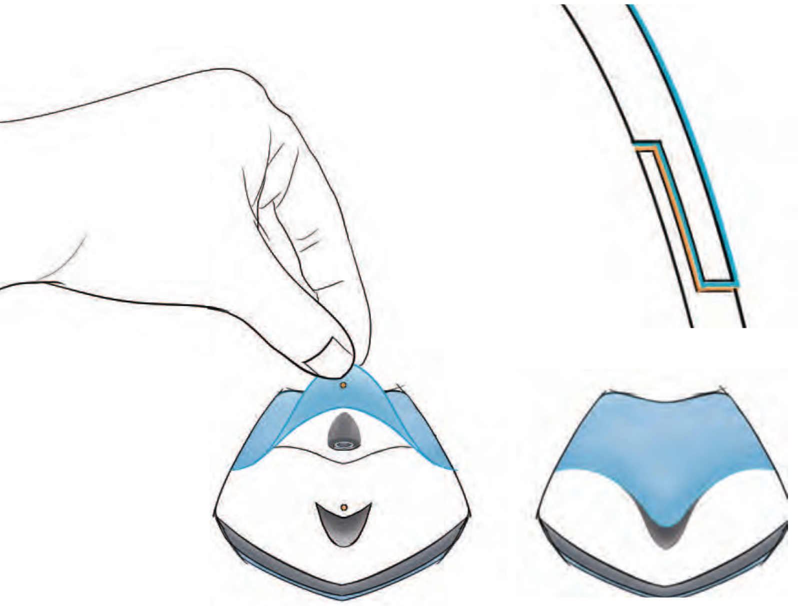
The adjustment hardware

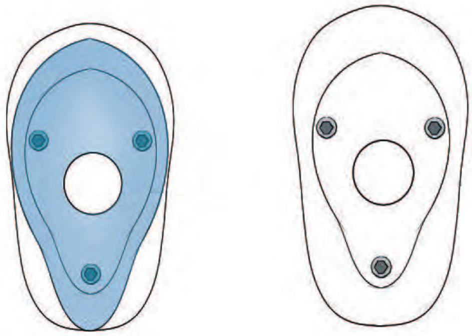
The top open

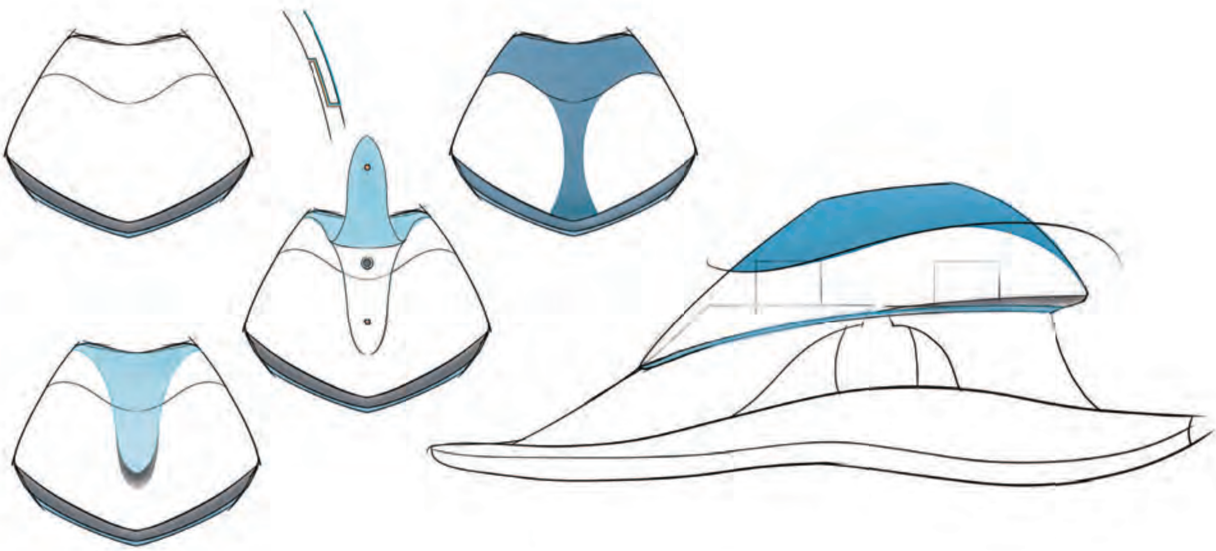
CREATING THE
PERFECT SEAL

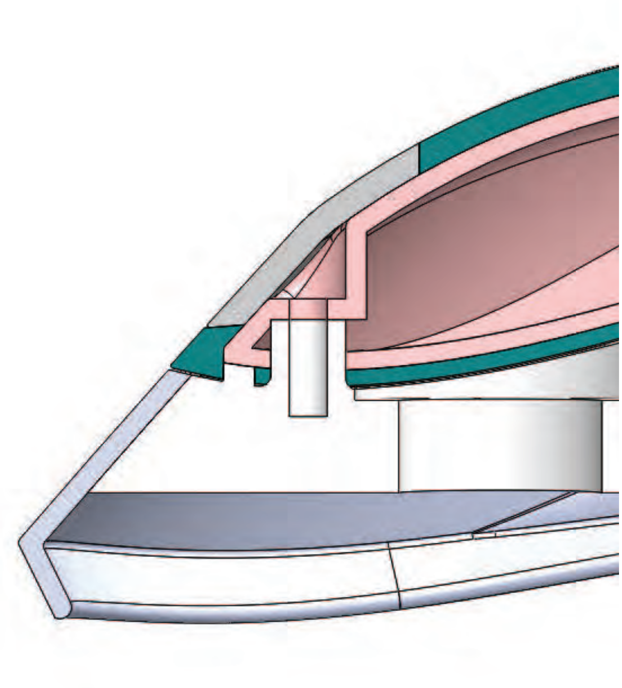


As the form developed, so did the functionality. We began to ideate various ways to keep the adjustment hardware dry. While it was possible to use an O-Ring, we determined the cleanest and easiest way would be to overmold part of the top.

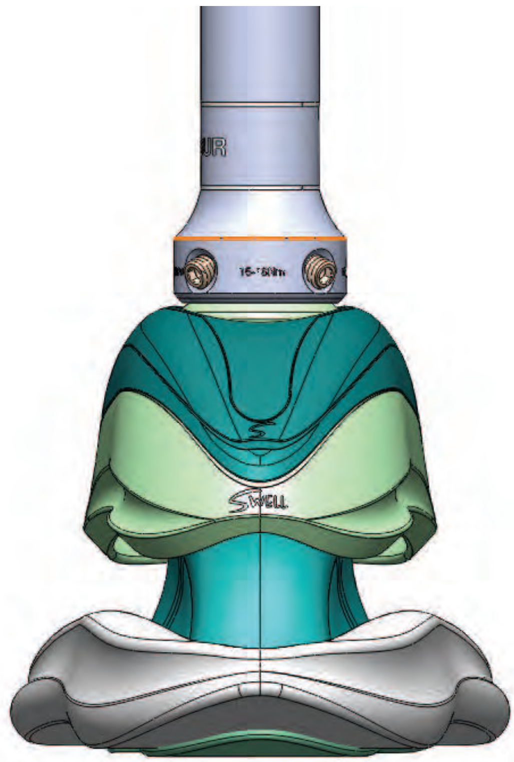




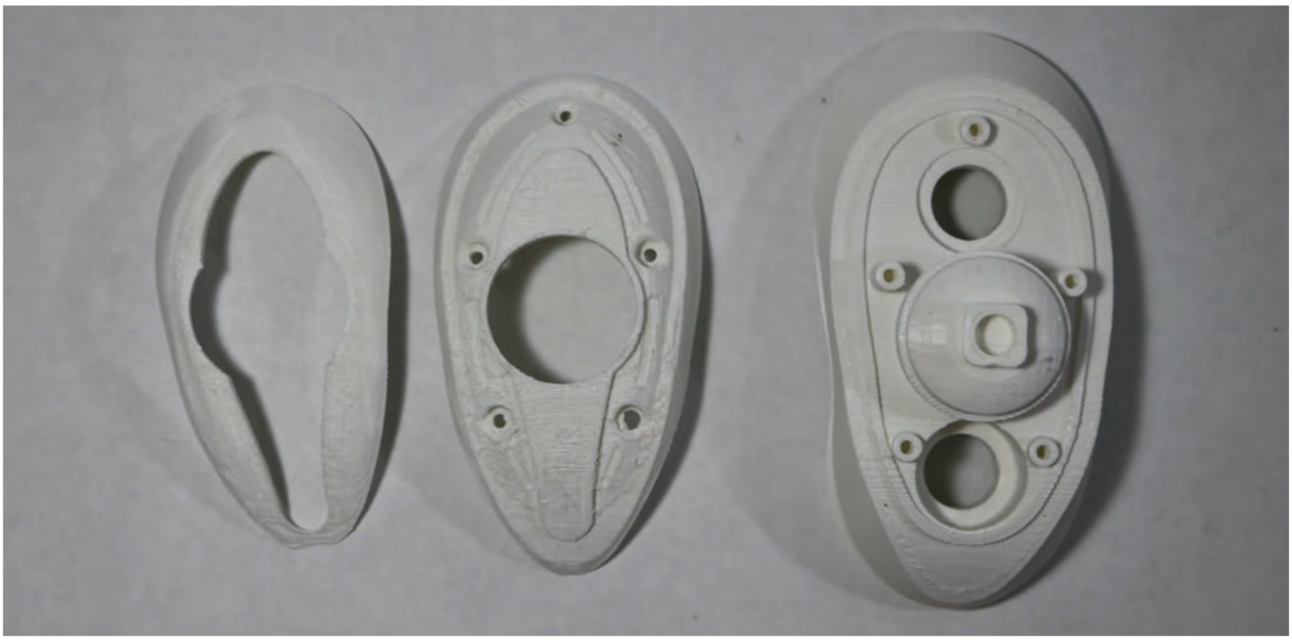




Creating the overmold in Solidworks



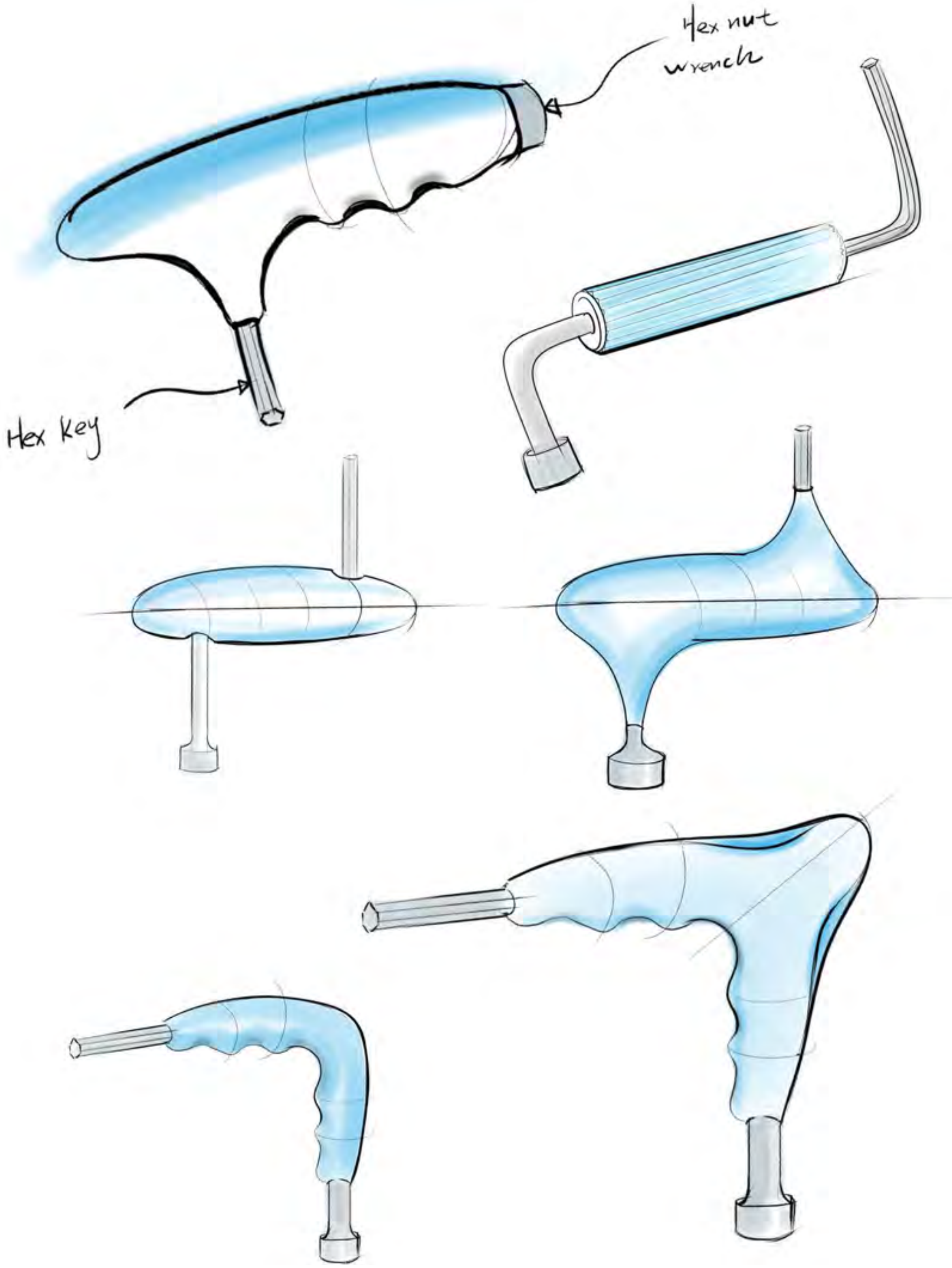
Creating the lift tab

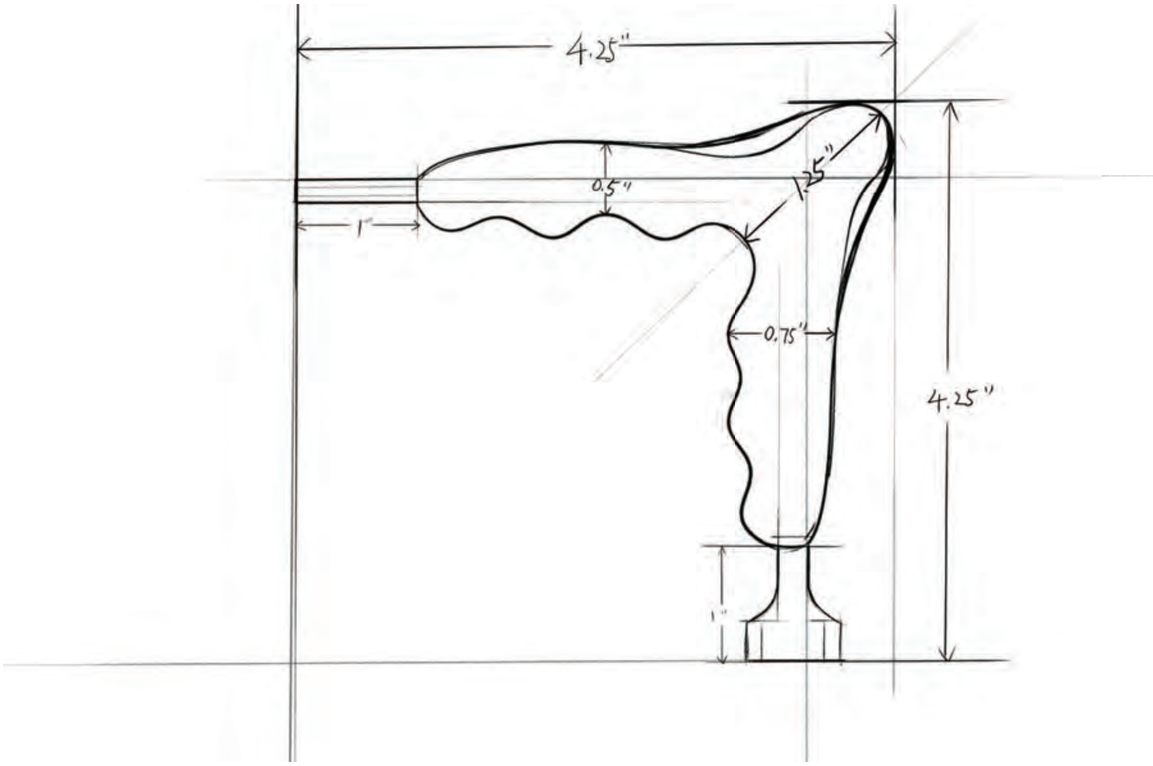


3D print, testing hole placement and split lines

ONE TOOL
FOR MULTIPLE FUNCTIONS

Once the seal on the top was designed we wanted the individuals using it to have an easy way to adjust everything with one tool. The tool would include the standard hex used on the pylon and our shell, as well as a socket to adjust the stiffness.

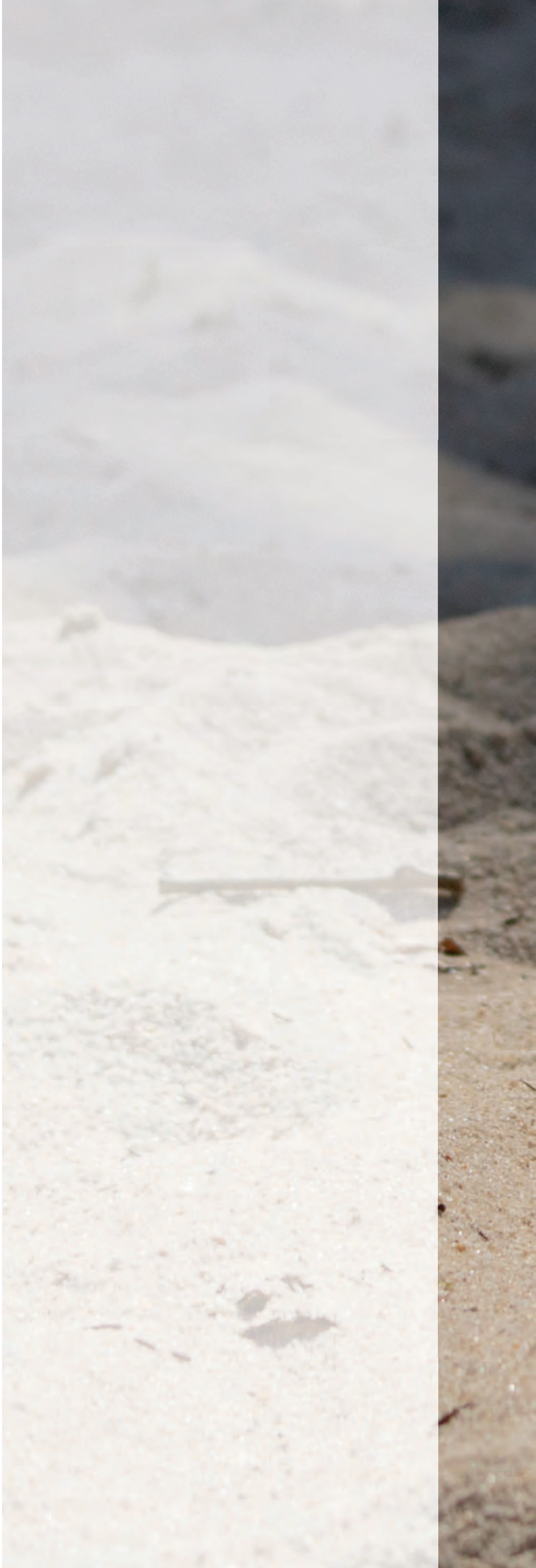




3D Print to test the ergonomics of the tool

ASSEMBLING IT
ALL TOGETHER

With the top shell completed, we were able to 3D print a top and assemble it together with the cast sole and bushing. The result is the final model that is ready to be tested in the ocean.




THIS IS THE
SWELL SURF FOOT
QUIKSILVER

A SWELL SURF SESSION

Designed for adaptability The Swell Surf Foot is ready to shred some waves. What's a day at the beach with Swell like? It's different than any other prosthetic experience. Let's take a look!

DESIGNED WITH THE SURFER IN MIND

Surfing is about freedom. The freedom to ride as many waves as you wish. The equipment you use shouldn't get in the way.

Swell was designed with amputees for amputees. It addresses the largest pain points that amputee surfers face every time they venture into the ocean. Swell gets out of the way and lets surfers do what they do best — shred some waves.

The Swell Surf Foot excels at quick, flexible movements in the ankle, something all other water prosthetics lack.

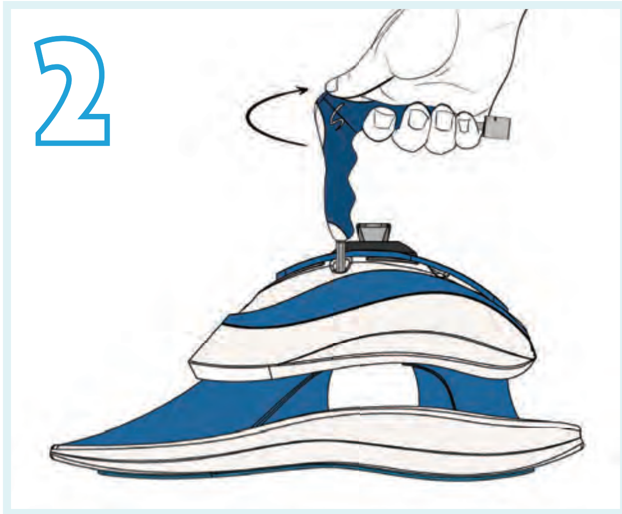
IT ALL STARTS
AT THE BEACH

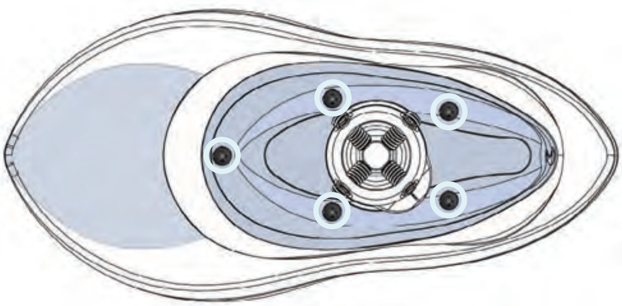
Swell is your surf leg. Swapping the leg on is easy and once equipped, nothing else is needed. Its **sand resistant** design **provides traction** allowing you to make your way to the ocean. When your surf session is complete, easily swap your Swell leg off and switch to your everyday leg.

SOMETIMES SOME
MAINTENANCE IS NEEDED

Maybe last session your foot felt too loose, or maybe the angle of the leg was slightly off. Swell was designed with **universal hardware**, that means one tool for the whole leg.

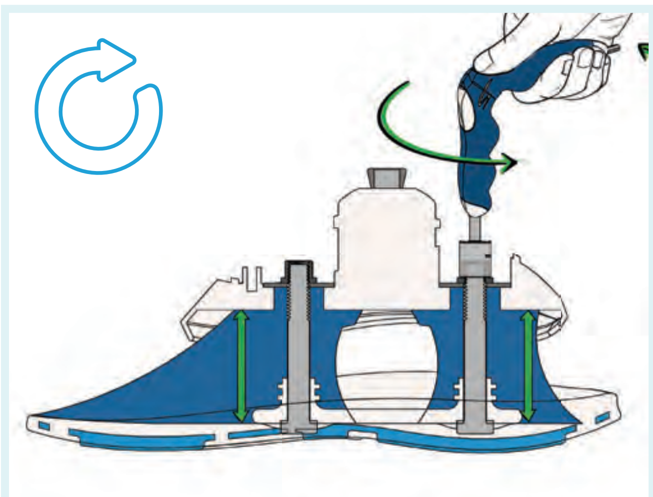
The standard hex screws found on pylons are the same size as the hardware on Swell, keeping a watertight seal.

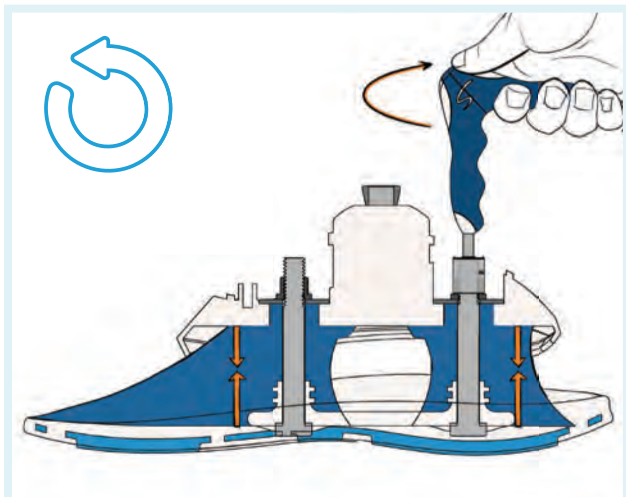




YOUR FOOT
YOUR PREFERENCES

Adjustability is key in a prosthetic. With Swell, the surfer has the ability to **alter the stiffness** of the bushings, based on their preference.





Removing the top, reveals two nuts for adjusting the bushing stiffness. Twist to the left to loosen and the right to tighten.

WALKING DOWN THE BEACH
HAS NEVER BEEN EASIER

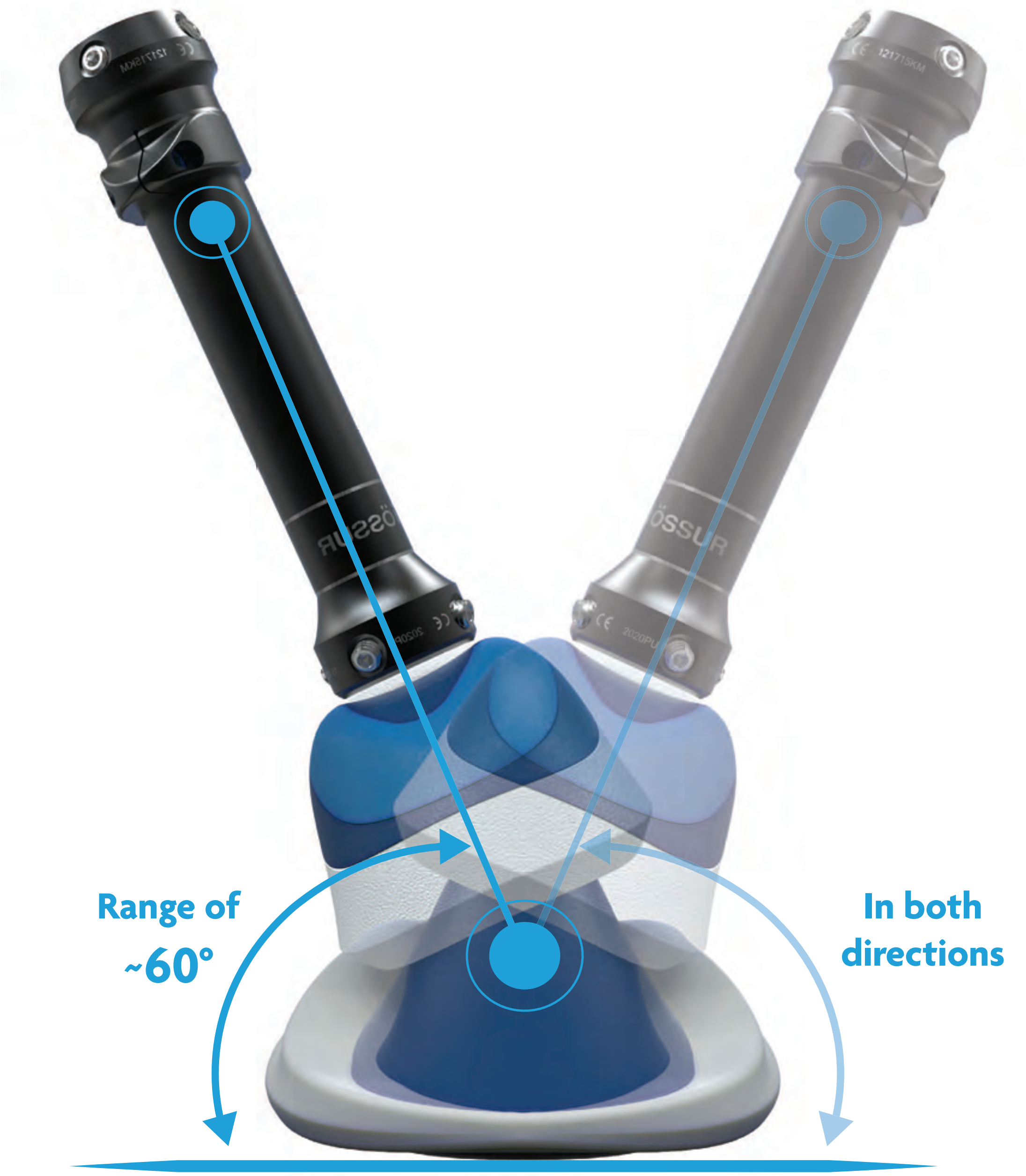
Swell's range of motion is powerful on and off the board. The soft sole provides comfortable plantar and dorsiflexion motion making walking feel natural, while also **absorbing shock.**

EXECUTING THE PERFECT POP-UP

No longer is an altered form needed to pop-up. The **flexible toe box** on Swell allows multiple degrees of flexion, allowing the foot to **stay flat** on the board. Whether you surf regular or goofy, Swell is able to adapt.

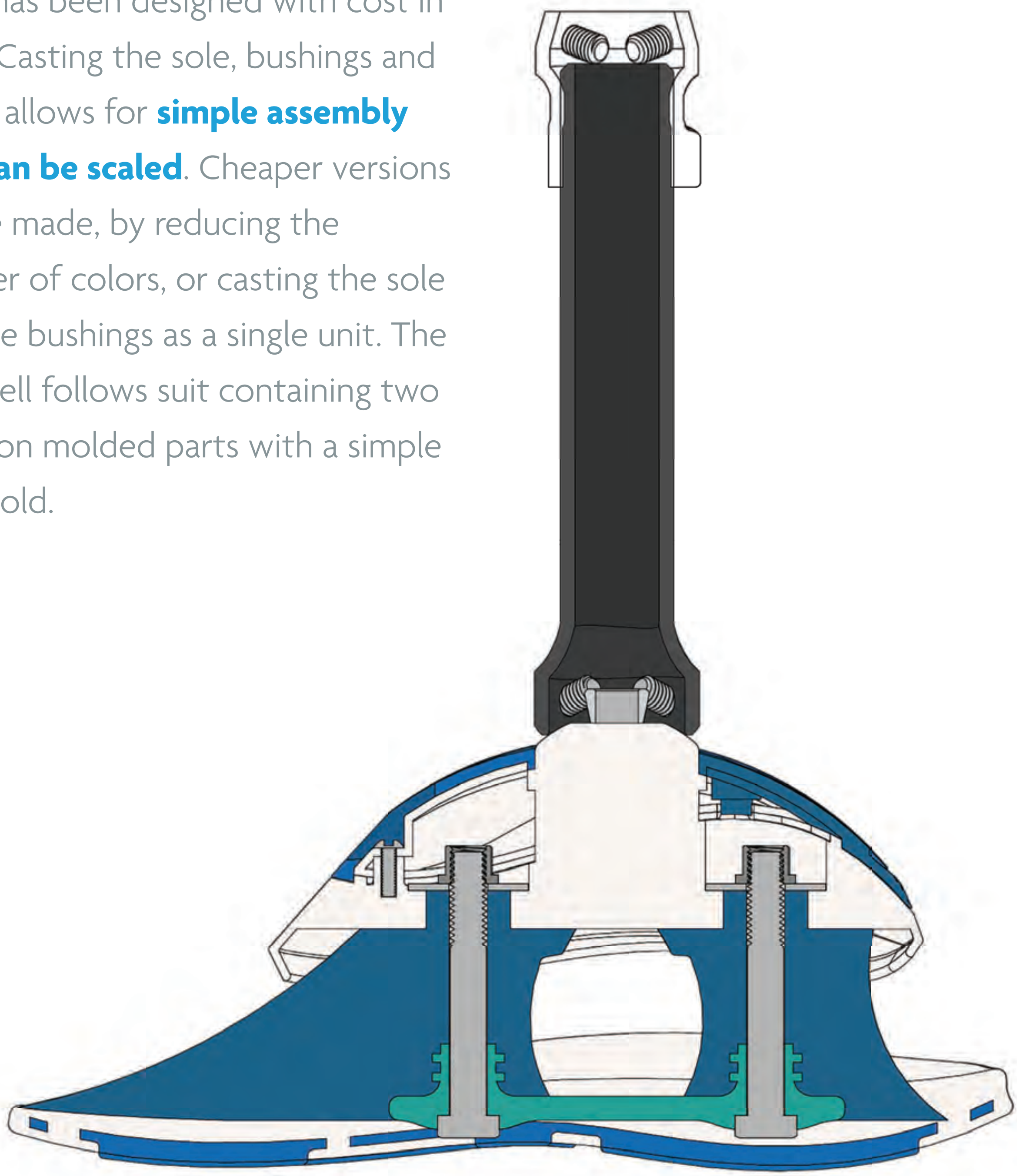
AN ANKLE THAT PERFORMS
THE WAY YOU NEED IT TO

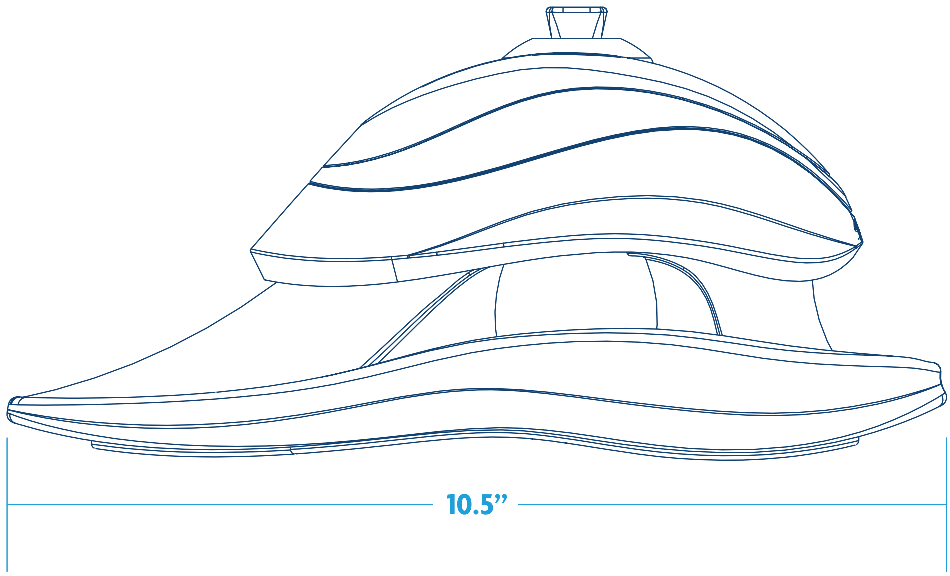
On the board the experience with Swell gets even better. Swell's motion in the abduction and adduction direction allow for **maneuvers unique to surfing.**



AFFORDABLE MATERIALS
PAIRED WITH SIMPLE PROCESSES

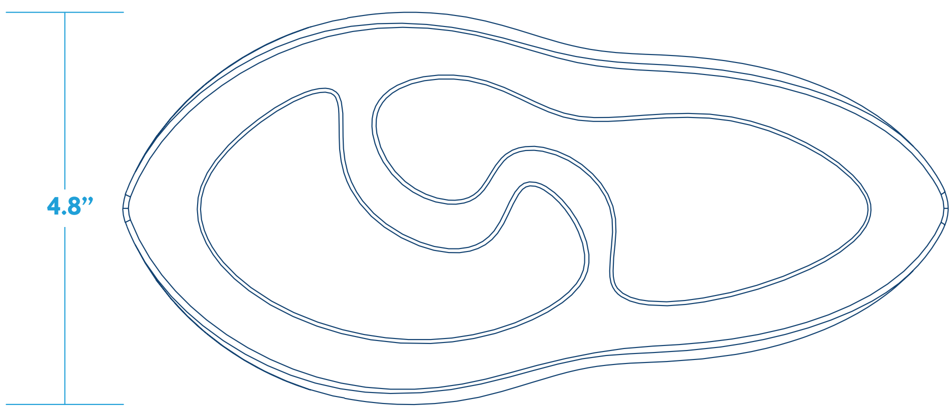
Swell has been designed with cost in mind. Casting the sole, bushings and treads allows for **simple assembly that can be scaled**. Cheaper versions can be made, by reducing the number of colors, or casting the sole and the bushings as a single unit. The top shell follows suit containing two injection molded parts with a simple overmold.





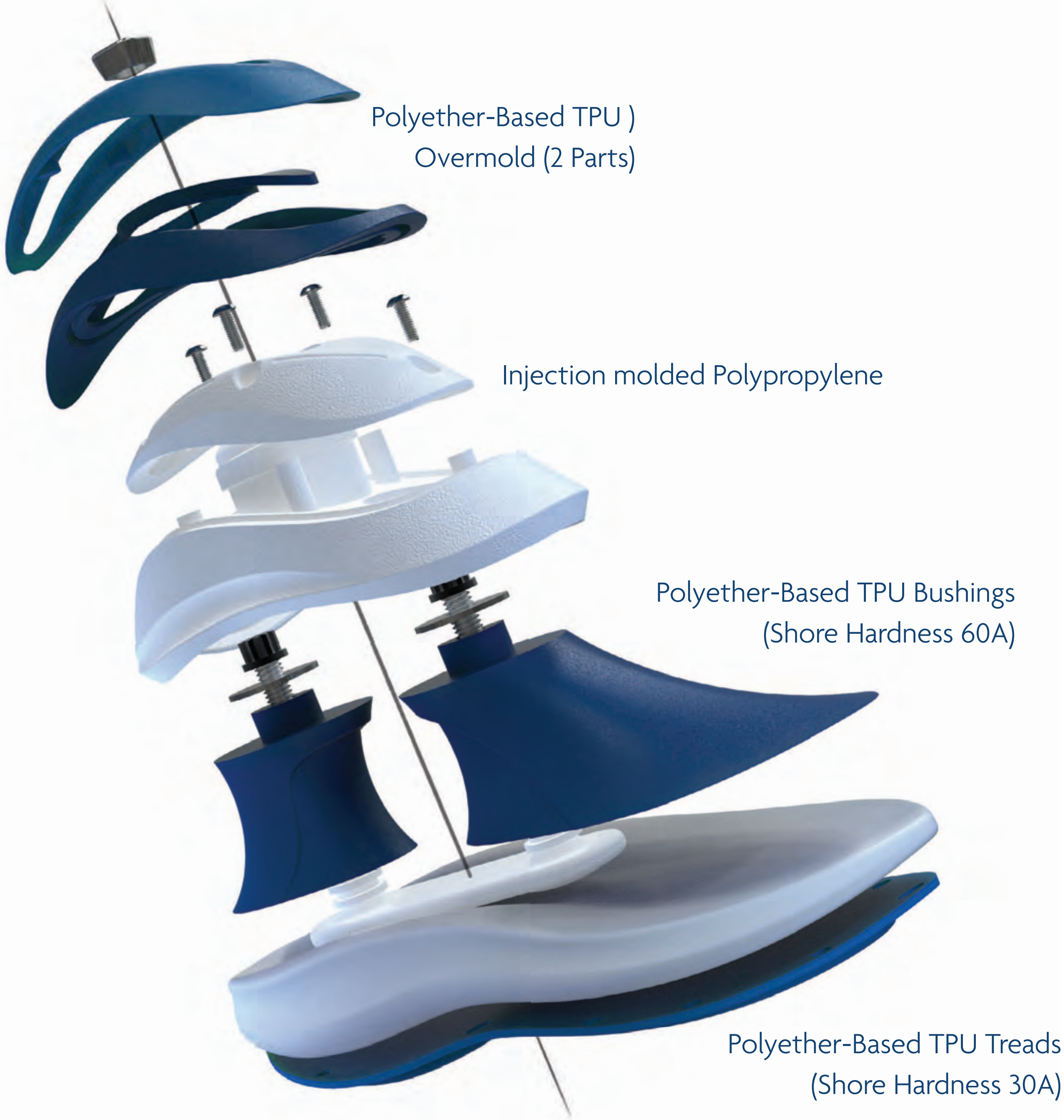
ONE FOOT
FITS ALL

We took the average men’s shoe size (10.5) and the average womens shoe size (8.5) and combined their overall lengths. The result is Swell’s **ambidextrous shape** that **weighs less than the average prosthetic**.



MADE WITH MATERIALS
TO WITHSTAND THE OCEAN

The ocean is rough, but Swell is tough. Consulting with Adam Deskevich of Knoll, allowed us to pick materials that could withstand repeated use under the **harsh conditions of salt water.**



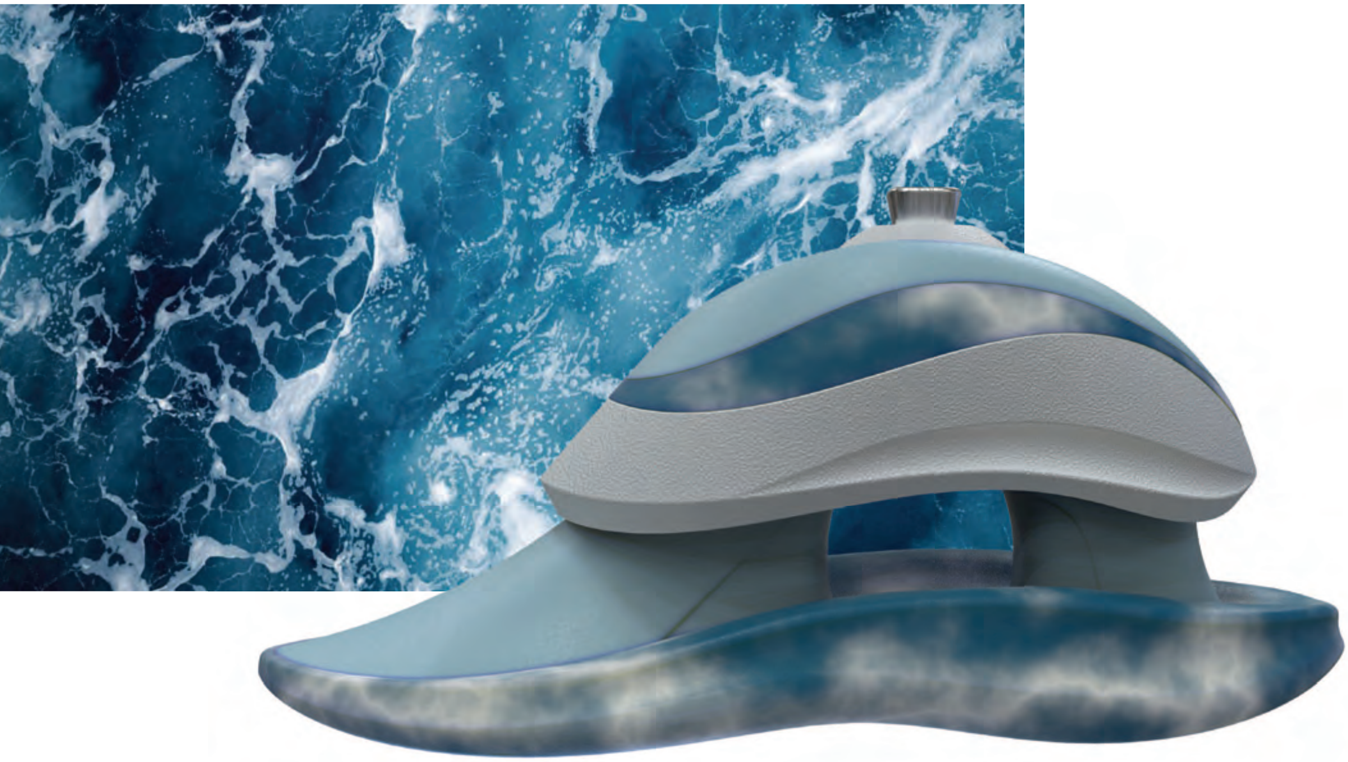

RedBull

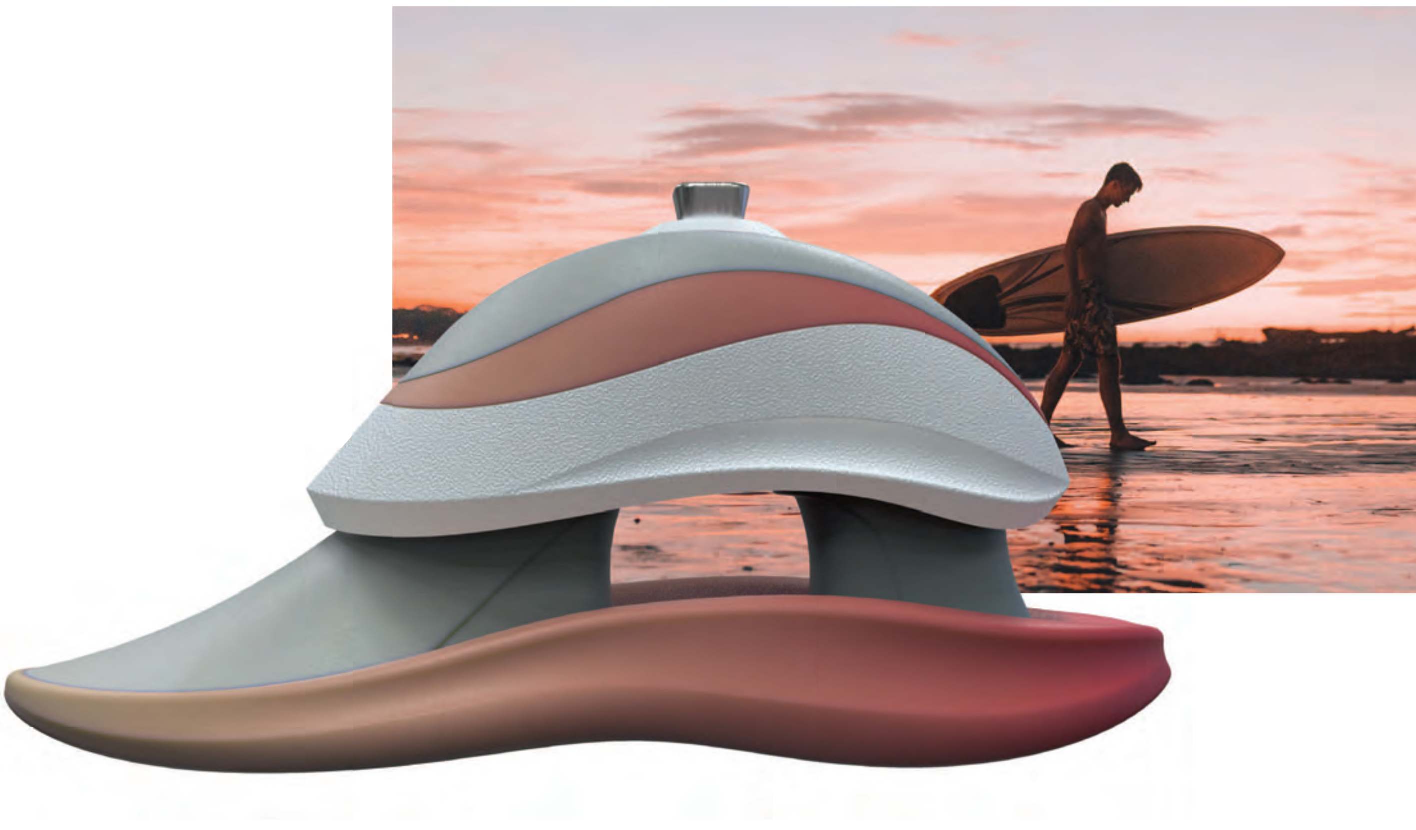
COLORS INSPIRED
BY THE SURFING CULTURE

A surfer's surfboard is a form of expression. Swell is an extension of that. Swell's construction allows for unique color options, that can be combined with traditional dye and coloring methods.

Casting the sole and bushings opens up the possibilities for gradients and textures, inspired by the ocean and sky.


PYZEL





THE FUTURE OF SWELL

The testing we achieved with Lance so far has helped validate the concept of Swell. In the future we hope to continue to work alongside our robust team of amputee surfers, to validate Swell's performance in the water and on the board.

Additionally we hope to explore other variations and sizes of Swell to target younger individuals who want to surf. The ocean is a therapeutic tool and everyone deserves access.

thank you...

To the surfers, the Industrial Design Department, industry professionals, colleagues, friends and family who have helped support this project from the start — it wouldn't have been possible otherwise.

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Todd Kramer

Tod Corlett

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Travis Ricks

Kevin Loughry

Chris Grimes

Adam Deskevich

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Ty Tucket

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Rodney Roller

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